C-CORE

Multi-year Ice Thickness Distribution in the Beaufort Sea Determined by Airborne Impulse Radar

Contract Report
C-CORE Publication No. 80-11
October, 1980

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The Centre for Cold Ocean Resources Engineering (C-CORE) was established at Memorial University of Newfoundland in St. John's in 1975. Its initial funding was provided by the Devonian Group of Charitable Foundations of Calgary. This support is being supplemented by grants from governments and industry.

The Centre's mandate is to undertake research that will assist the safe and orderly development of Canada's resources in which cold and ice frequented oceans are a problem. C-CORE's main concentration of research is on ice, its properties, detection and behaviour.

ABSTRACT

The possibility of using airborne impulse radar to characterize multi-year ice in the Beaufort Sea was investigated in March 1979. This was the first recorded use of a sea ice sounder from a fixed-wing aircraft. A total of 440 line-km of data were examined, along with simultaneous aerial photography.

Initially aided by high and low level photography, analysis of impulse radar data can now be used to differentiate between first-year and multi-year ice. Multi-year ice covered 55% of the line studied, and a total of 11% of the multi-year ice (27 km) showed impulse radar bottom echoes. The maximum thickness penetrated was 13.5 m, while a minimum thickness was imposed by the waveform of the transmitted pulse at 1.3 m. Bottom echoes were sporadic, and deformed ice appears more difficult to penetrate, but further studies will have to be done before these limitations are fully understood.

An ice thickness distribution based on the multi-year ice penetrated had a peak at 3.4 m and a mean thickness of 3.7 m. The distribution curve fits a negative exponential for ice thicknesses greater than 4.0 m with an exponential coefficient of -0.62, significantly different from the value of -0.37 reported from previous analysis of submarine sonar keel drafts in the Beaufort Sea.

ACKNOWLEDGEMENTS

Financial and logistic support for the collection of these data was provided by Canadian Marine Drilling Limited and Esso Resources Canada Limited. In particular, Dr. J.B. Mercer of CanMar participated directly in planning and excuting the experimental work and made many useful suggestions on the data analysis. Mr. L.G. Spedding of Esso collected and analysed the high level aerial photography. Encouragement from Dr. P.R. Kry of Esso was also appreciated.

Additional financial support for the C-CORE field trip to the Beaufort Sea came from the Department of Supply and Services, Canada, Contract 1SU78-00347. Logistic support from Polar Continental Shelf Project for the researchers collecting the data, and technical support from the National Research Council of Canada for the antenna radiation patterns, are both gratefully achnowledged.

C-CORE would like to thank all of the above organizations for this opportunity to develop ice sounding radar technology. It is hoped that this work will assist in making airborne ice thickness measurement a more routine tool for polar operations.

This work was carried out by the following C-CORE personnel:

James Rossiter - project management; field measurements; data interpretation and report preparation;

Jan Snellen - data analysis and interpretation; report preparation;

Ken Butt - equipment preparation and installation;

Terry Ridings - equipment installation and camera operation.

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INTRODUCTION

In March 1979, C-CORE personnel were in the Tuktoyaktuk area of the Beaufort Sea for Arctic trials of airborne impulse radar for sounding sea ice (Appendix 1). At the initiation of Dome Petroleum, through its subsidiary Canadian Marine Drilling (CanMar), a survey was carried out to estimate the thickness distribution of multi-year ice using impulse radar. Esso Resources Canada became a partner in the project, and were responsible for collection of high level stereo photography.

This experiment demonstrated the first recorded use of impulse radar from a fixed-wing aircraft, a Twin Otter. Simultaneously, the high level stereo photography was collected from a second Otter flying above the radar aircraft. The impulse radar data were plotted in real time in the aircraft and were also recorded on magnetic tape for later playback and analysis. Some low level photographs were also taken from this airplane.

The data were analyzed to determine the impulse radar's ability to distinguish between different ice types using the photography as a guide, to evaluate the penetrating ability of the airborne impulse radar, and to calculate a thickness distribution curve for the multi-year ice that was penetrated. This sort of information is required for planning of offshore industrial operations in the Beaufort Sea.

DATA COLLECTION

Equipment Installation

For collecting the data two de Havilland Twin Otters were used: one flown at low level with the ice sounding radar; a second flown simultaneously at higher altitude to take high quality, stereo photographs. The low level Otter contained the impulse radar equipment with its antenna mounted on the fuselage, a downward-looking 70 mm camera, and facility for recording voice notes. The impulse radar data were recorded both on analog magnetic tape and on a Honeywell visicorder. The latter required 110 volts AC power, which necessitated installation of a small generator, vented to the outside. The rest of the equipment was powered from the aircraft 28 volt DC supply. System specificiations are given in Tables 3 and 4 of Appendix 1.

The impulse radar antenna (GSSI Model 3105A) was mounted directly behind the nose wheel as shown in Figure 3 of Appendix 1. The antenna package contained a pair of antennas set side-by-side: one transmitting and one receiving. The radiated electric field was perpendicular to the direction of flight. Each antenna was shielded with a hyperbolic plate to reduce reflections from the aircraft body. Although this antenna has low back radiation, it has fairly omni-directional radiation characteristics downward, as shown in Appendix 2. One of the major effects of the shielding is that the pulse transmitted has a relatively long decay time of 16 ns as shown in Figure 1. This waveform therefore cannot be used to sound ice much less than about 1.3 m thick.

The impulse radar system, as rented from GSSI, had a mismatch between the antenna element, which had a 300 MHz centre-frequency (Appen-

Figure 1 The direct wave is the pulse that travels directly from the transmitting to the receiving antenna. The surface echo is the reflection of the pulse from the ice surface (in this case smooth level ice). Both these returns give some idea of the shape of the transmitted pulse. The 16 ns decay time obscures bottom echoes less than about 1.3 m thick.

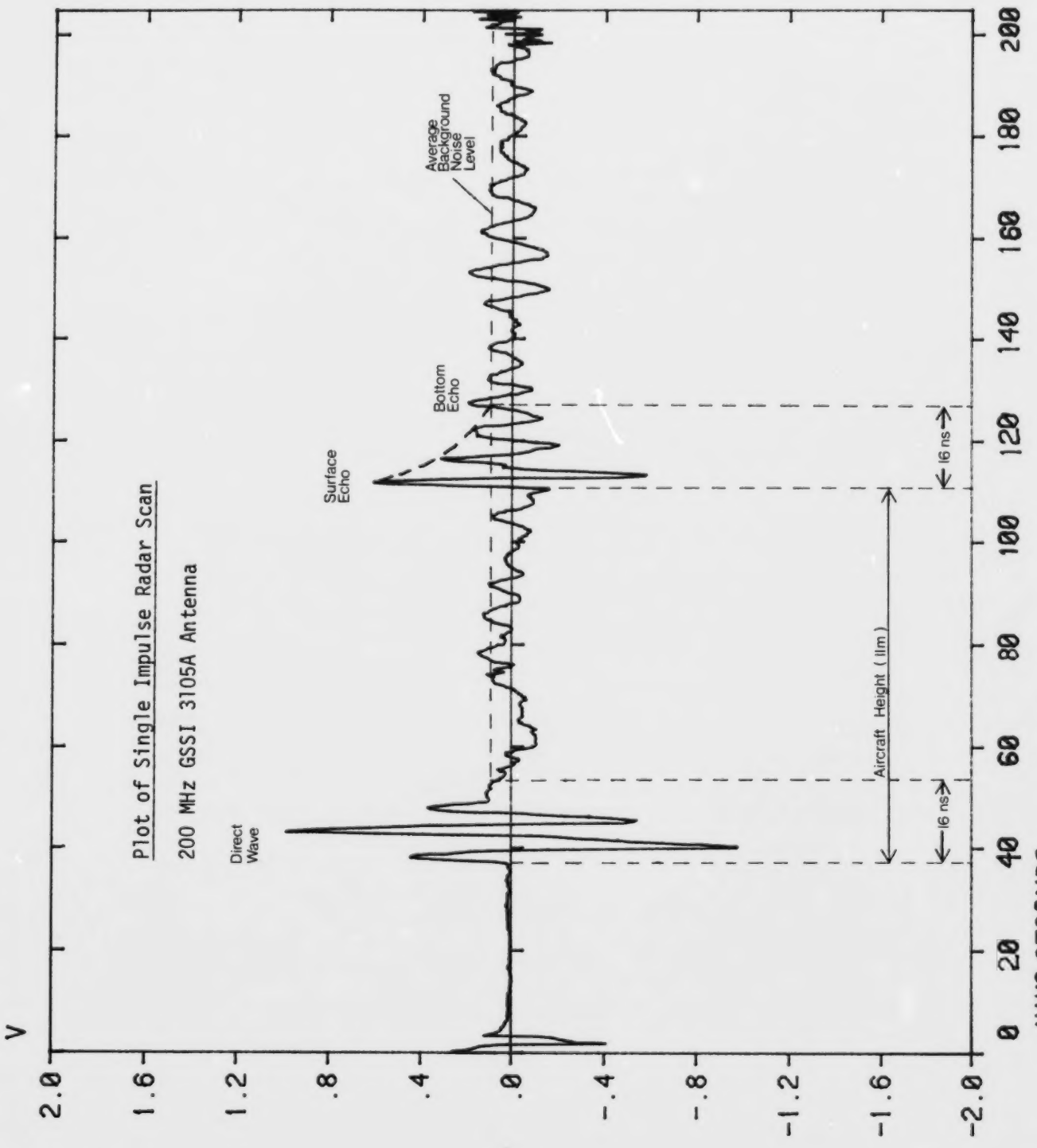


Figure 1

dix 2), and its electronics, which had a 200 MHz centre-frequency. This problem was only determined after data collection, but may partially explain the limited penetration of this particular installation. More recent work shows that other GSSI systems have significantly greater penetration capability (Butt and Gamberg, 1980).

Equipment in the cabin consisted of the control unit for the GSSI impulse radar, a power supply - camera controller - voice note recorder fabricated by C-CORE, a Racal Store-4D analog instrumentation tape recorder, and a Honeywell 1856A visicorder with Model 1219 dry silver paper processor. The latter device produced hard-copy sounding data in the aircraft with approximately one minute delay.

A Hasselblad Model EL500 70 mm camera, with 40 mm lens and Model 500 750-exposure back, was mounted in the camera bay. Additional hot air had to be directed toward the camera for it to operate consistently. Communication was available through headsets between the observer and the camera operator, and all voice comments were recorded on two separate channels of a cassette tape recorder.

Operational Procedure

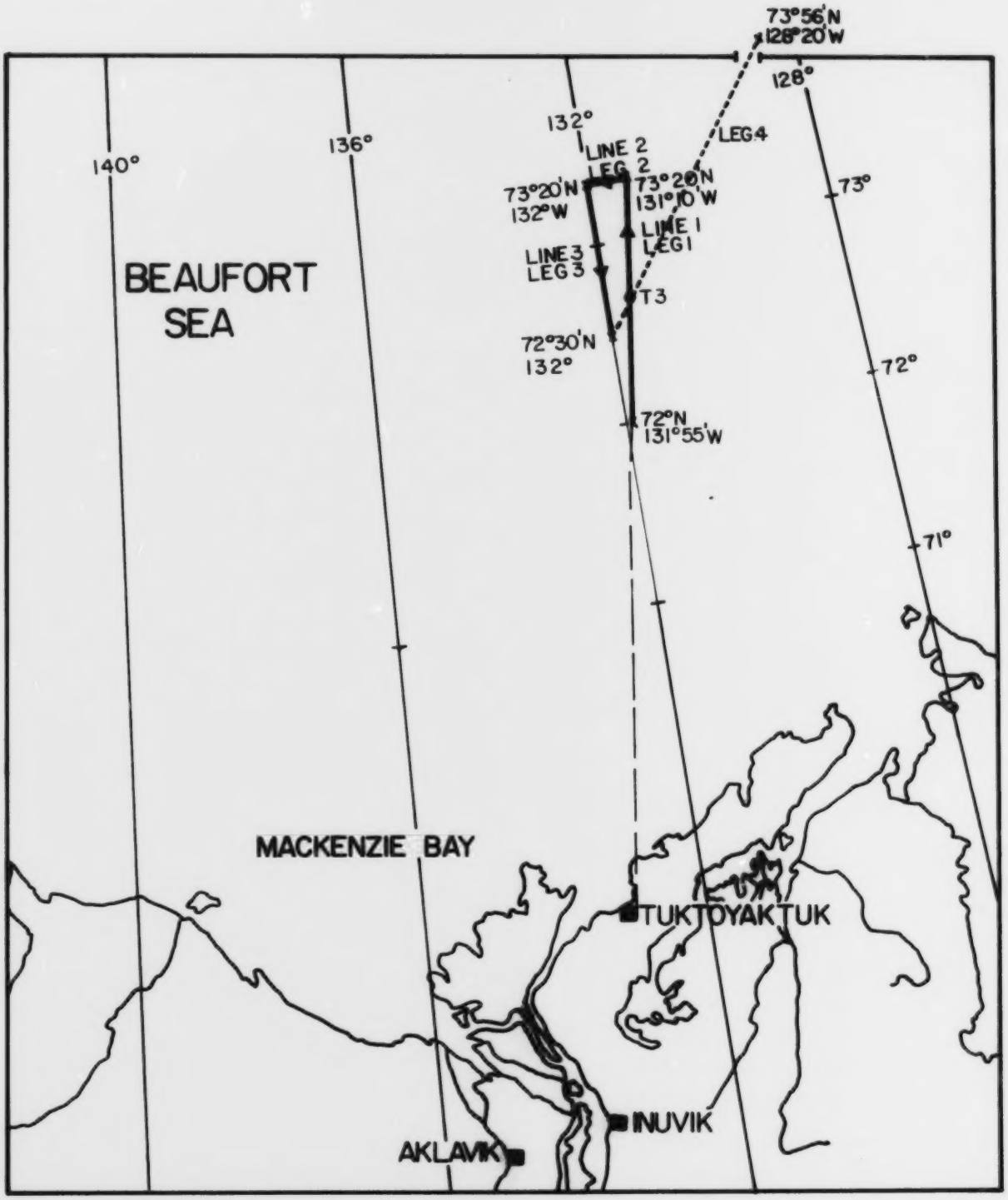
Three personnel plus the pilot were carried in the lower Otter during data collection: a radar operator and a camera operator (C-CORE), and an ice observer (CanMar). The aircraft was chartered from Borek Air Services, Inuvik. In the high altitude Twin Otter, owned and operated by Esso Resources Canada, high resolution stereo photography were collected using a Fairchild F-17 9" mapping camera with a 6" lens. The flights of the two aircraft were co-ordinated so that as much simul-

taneous aerial photographic coverage could be taken over as much multi-year ice as possible. The limitation was the flying time available on the Esso Otter, approximately four hours total.

Data were collected on two separate days: March 14 and 17, 1979, as summarized in Table 1 and Figure 2. For Day 1, the lower aircraft flew at approximately 250 feet (75 m) and approximately 140 knots (70 m s^{-1}); for Day 2, at 100 feet (30 m) and 100 knots (50 m s^{-1}). The lower elevation appeared to provide greater penetration capability, and the lower speed provided greater horizontal resolution. The higher aircraft was flown at 8,000 feet (2440 m), simultaneously with the lower aircraft, and took photographs every 21 seconds, providing 70% overlap at 1:16,000 scale. Layers of haze and clouds came between the two aircraft on Day 1. Because of this poor visibility and the poorer impulse radar data quality, only Day 2 data have been analyzed in detail.

Low level photographs were taken to be able to distinguish detailed ice features. Once per minute, a set of ten exposures was taken at a rate of one frame every two seconds (approximately one frame every 100 m, at 100 knots). At 30 m (100 feet) elevation each frame covers approximately 43 m per side. Marks were to be placed automatically in the radar record when each photograph was taken, but this feature failed shortly after the beginning of the run.

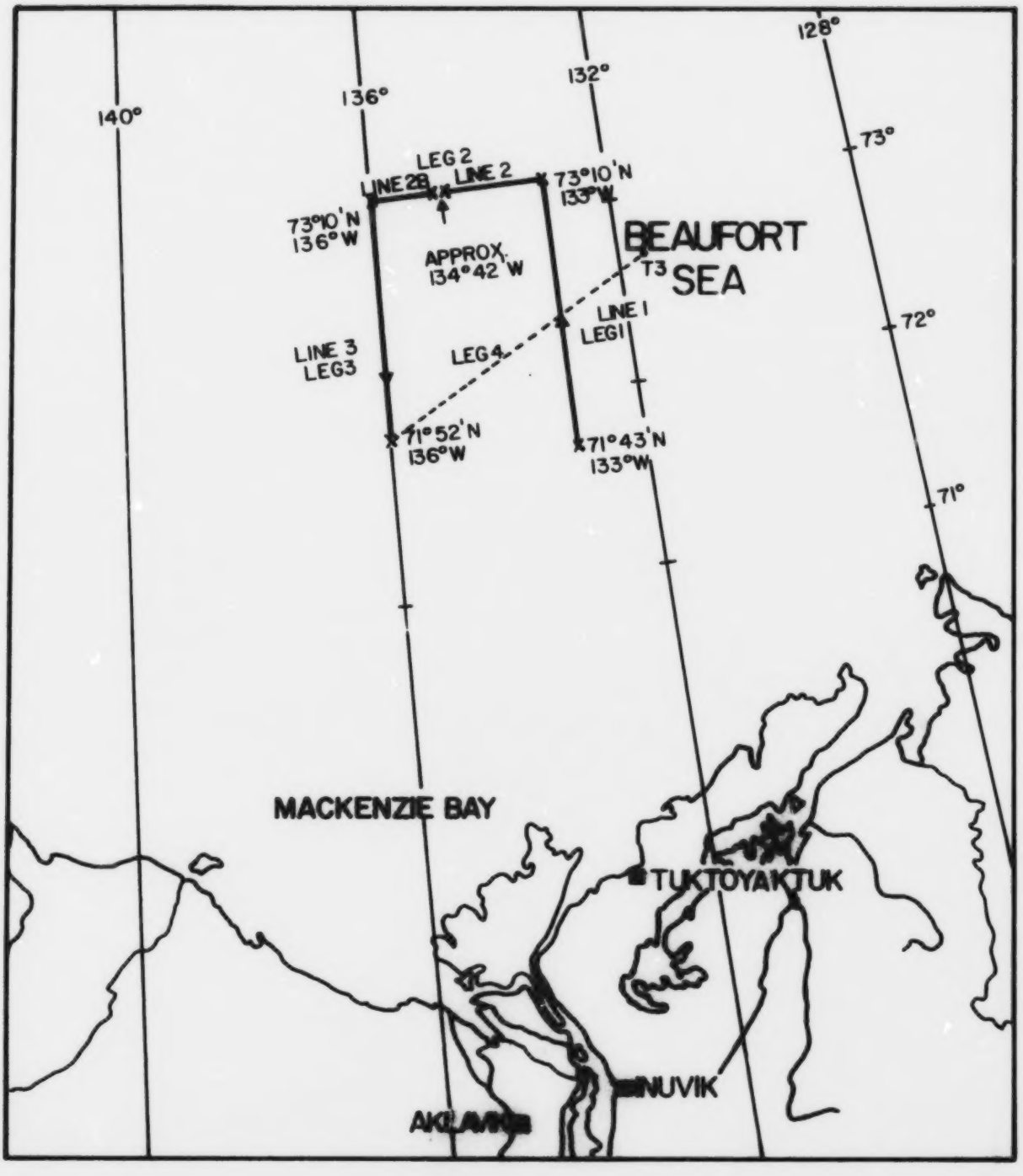
For Day 2 there are approximately two-and-a-half hours of data recorded on tape, equivalent to 440 km. The data were collected on the three legs as shown in Figure 2B, and radio co-ordination was made with the upper aircraft at each turning point. The photo log for the stereo photos is given in Appendix 3. Note that only 407 km of high level photography were taken, because of the turns and a film change.



LOCATION OF FLIGHT LINES FOR 790314 FLIGHT.

Figure 2A

------- Impulse Radar Data Only



LOCATION OF FLIGHT LINES FOR 79 03 17 FLIGHT.

Figure 28

------- Impulse Radar Data Only

Table 1. Multi-year Ice Distribution Study: Summary of Operation

Date (1979)	March 14 (Day 1)	March 17 (Day 2)
Radar Altitude	250 ft (75 m)	100 ft (30 m)
Airspeed	140 knots (70 m s^{-1})	100 knots (50 m s^{-1})
Low-level Photos	696 photos	1064 photos
High-level Altitude	8000 ft (2440 m)	8000 ft (2440 m)
High-level Photos	Trouble keeping lower aircraft in view	151 photos 220 nautical miles (407 km)
Weather Conditions	Hazy	Clear
Location (approx.), flight direction	72^{o} 30'N 131^{o} 55'W, 010^{o}T 73^{o} 20'N 131^{o} 10'W, West 73^{o} 20'N 132^{o} 0'W, South 72^{o} 30'N 132^{o} 0'W, end	71^{o} 43'N 133^{o}W, North 73^{o} 10'N 133^{o}W, West 73^{o} 10'N 136^{o}W, South 71^{o} 52'N 136^{o}W, end
	(see Figure 2A)	(see Figure 2B)

Note: Analysis to date has only used data from Day 2.

An additional half-hour of data was collected over the surface truth site prepared during the SURSAT experiment (see Appendix 1), at three different altitudes: 50, 100 and 150 feet (30, 60 and 90 m). The remainder of that tape covered a large portion of ice island T-3. Later in the month the surface truth site was also profiled using an 80 MHz GSSI system (see Figures 4 and 5 of Appendix 1).

DATA PROCESSING

The data, recorded on analog tape using the four-channel instrumentation tape recorder, consisted of impulse radar scans recorded in both FM and direct modes, the impulse radar system clock, and a tape servo signal for accurate playback. The impulse radar data recorded in the direct mode was used for analysis because of its larger recording bandwidth. All data tapes were played back and plotted using the Honeywell visicorder.

To create a plot of the impulse radar data that is interpretable to the human eye, the visicorder plots each impulse radar scan as a line. Variable intensities of white and black along the line represent the variable amplitudes of positive and negative voltages respectively along the scan. For example, a large amplitude negative voltage peak is represented by a dark segment on the line. Grey tones represent voltages near zero. By plotting consecutive scans, aligned and close together, a two-dimensional plot is obtained showing, in the vertical direction, the ice surface and sub-surface relief, and, in the horizontal direction, distance along the flight line (Figure 3A).

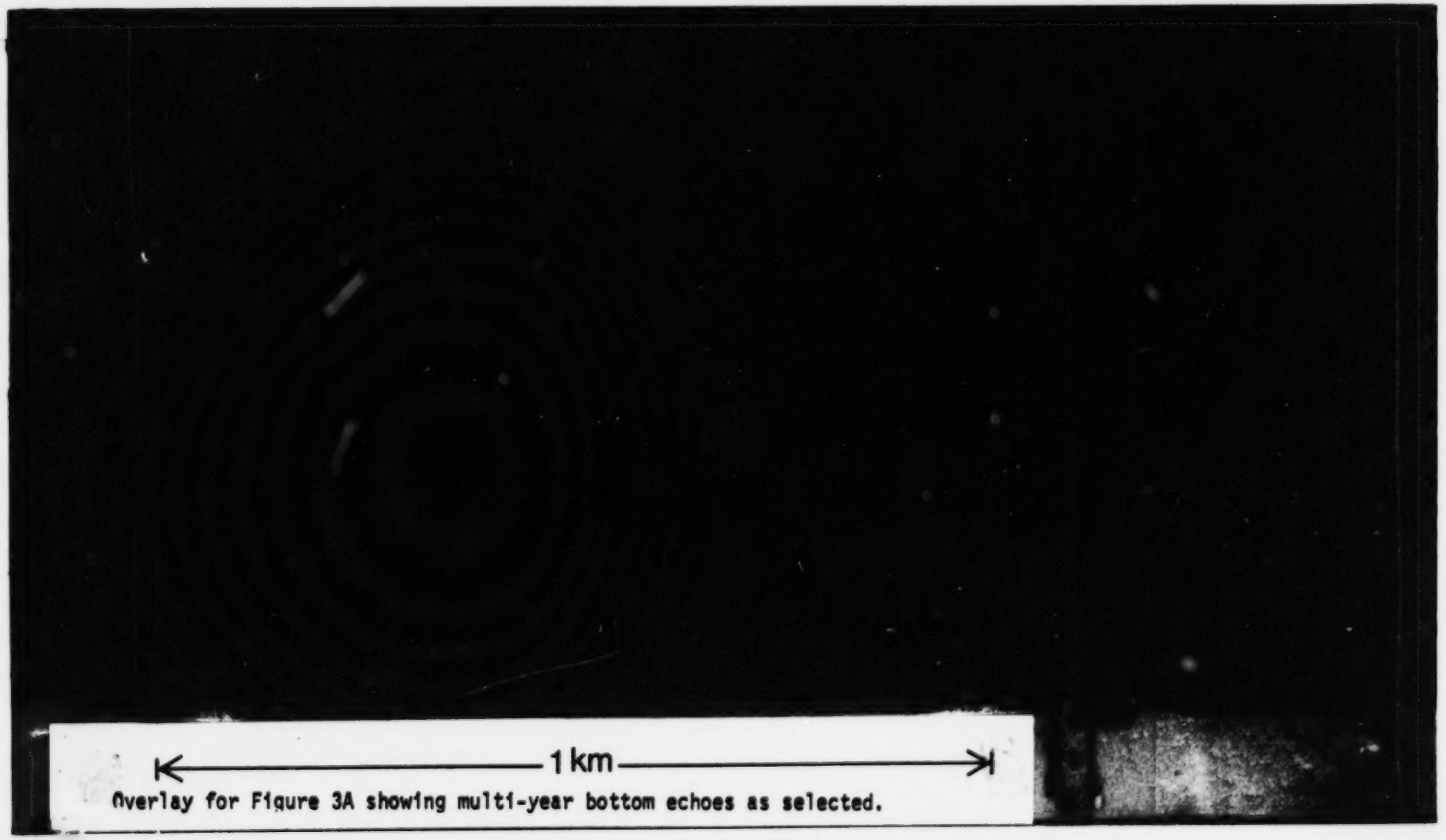
All the impulse radar data for Day 2 of this experiment were recorded (and printed in real-time) using a 500 ns window with offset. A 500 ns window indicates that echoes with delay times up to 500 ns after the start of scan are recorded. The start of scan can also be offset in time from the transmitted pulse in order to avoid plotting some of the travel time through the air before receiving the ice surface return.

The 500 ns vertical scale was too small for accurate analysis of bottom returns; therefore on playback only the first 200 ns of each scan

were plotted. The horizontal scale was also expanded by increasing the spacing between consecutive scan lines. On the average about 10% of the 200 ns vertical window was travel time through air, and the 180 ns remaining for ice (representing approximately 15 m) was sufficient to avoid missing any bottom echoes.

At present, airborne impulse radar data includes background noise and reverberation. An attempt was made to filter the data to reduce these effects. Bandpass filtering, which has been used successfully on other impulse radar data, was unsuccessful with this data set because the frequency ranges of the data and the ringing were similar. Background noise removal was not particularly helpful, and, at the moment, is quite laborious. Several computer-based enhancement procedures are being developed, but were not used for this analysis.

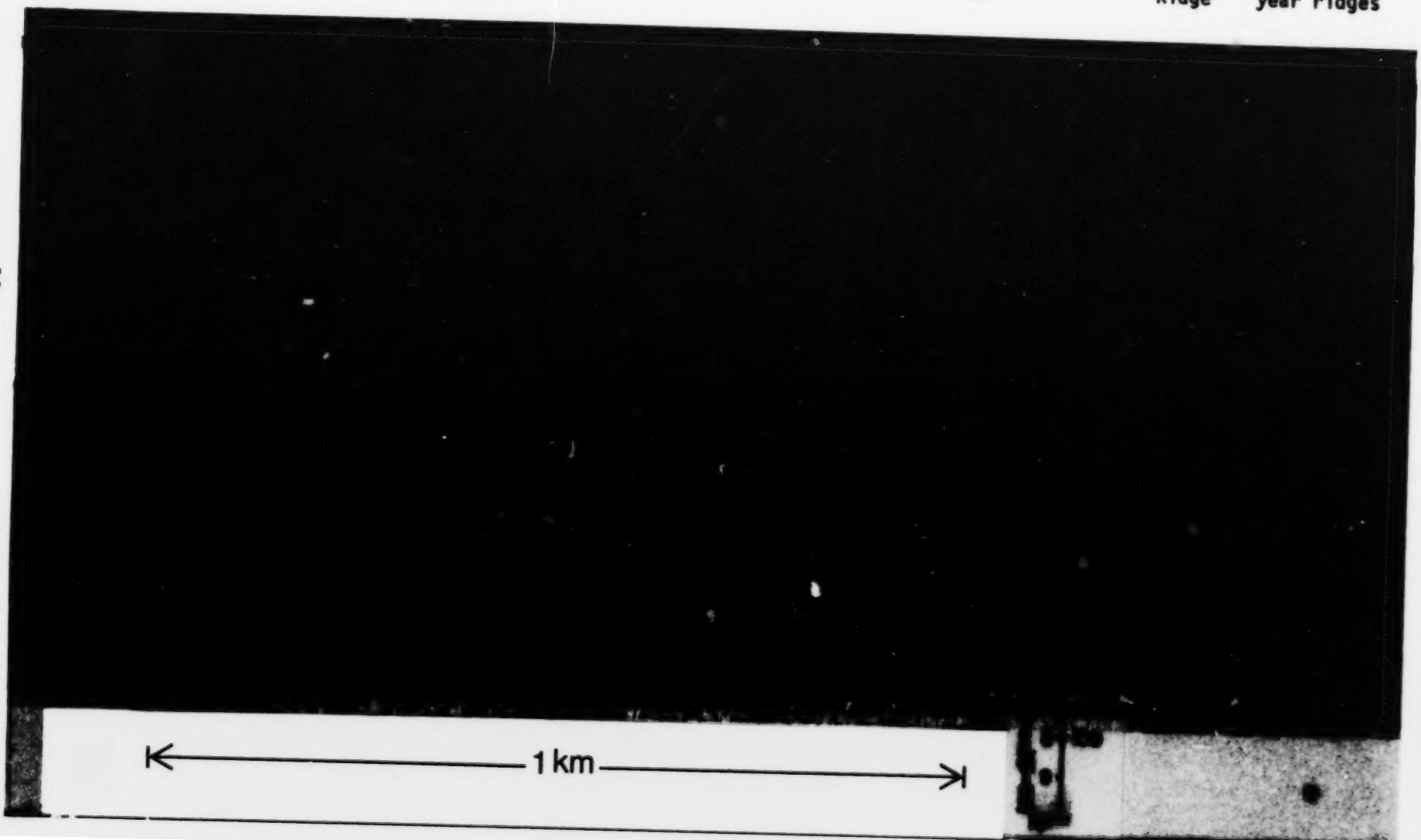
Visicorder plot of impulse radar data recorded over multi-year ice in the Beaufort Sea with ice feature interpretation. Features marked by symbols on the plot correspond to features marked by the same symbols on the accompanying high level photograph, Figure 3B. Boxes along top left-hand edge indicate low level photographs (Figure 3C).



Overlay for Figure 3A showing multi-year bottom echoes as selected.

Figure 3A Example of Impulse Radar Data Plot

Visicorder plot of impulse radar data recorded over multi-year ice in the Beaufort Sea with ice feature interpretation. Features marked by symbols on the plot correspond to features marked by the same symbols on the accompanying high level photograph, Figure 3B. Boxes along top left-hand edge indicate low level photographs (Figure 3C).



DATA ANALYSIS

Ice Type Determination

In developing a procedure to distinguish first-year and multi-year ice using impulse radar, the high level photography proved to be of tremendous help. First-year and multi-year ice can be reliably recognized from good high level photography. Features such as a flat, smooth upper surface, well-defined rough ridges, and floes with sharp corners, straight edges and cracks, characterize first-year ice. Weathered ridges and hummocks, an undulating surface, and rounded floes are multi-year ice characteristics observed from the photography (Figure 3B).

By plotting the flight line of the lower aircraft onto a mosaic of the high level photographs, a direct correlation was established between the photography and the impulse radar plot to be interpreted. The photography and the radar plot for the first leg of Day 2 (about 100 km) were compared in this way, to obtain some descriptive characteristics of the top and bottom surfaces of the ice as represented on the impulse radar plot.

Impulse Radar features from first-year ice were:

(1) undeformed first-year ice had a very flat top surface echo;

(2) first-year ridges in general were very steep and gave a weak radar return from the top surface because the broken ice scattered the signal (this scattering also prevented the detection of bottom returns from first-year ridges);

(3) in most cases the ice bottom was not detectable, because the minimum thickness that could be sensed was about 1.3 m (specific for this system);

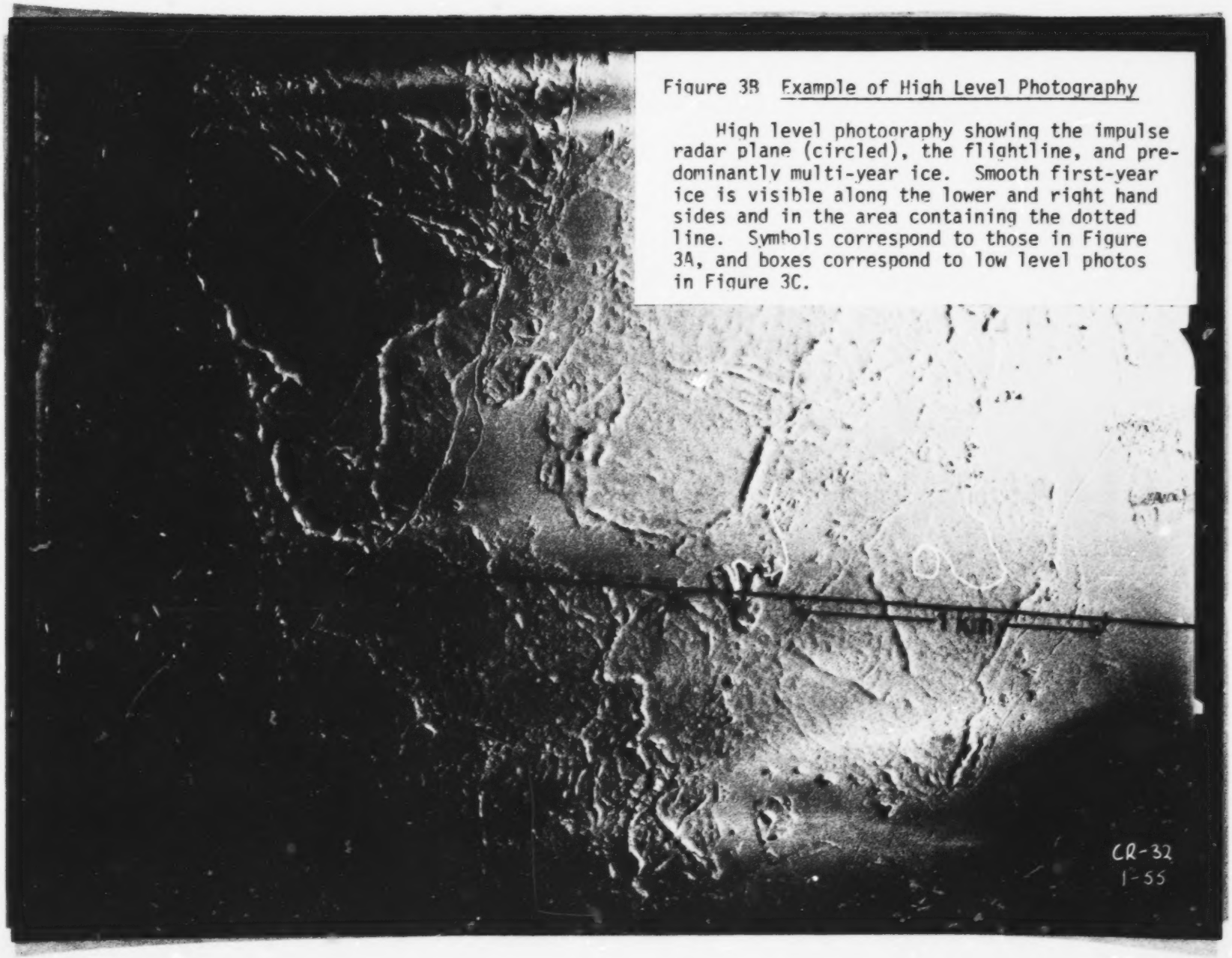
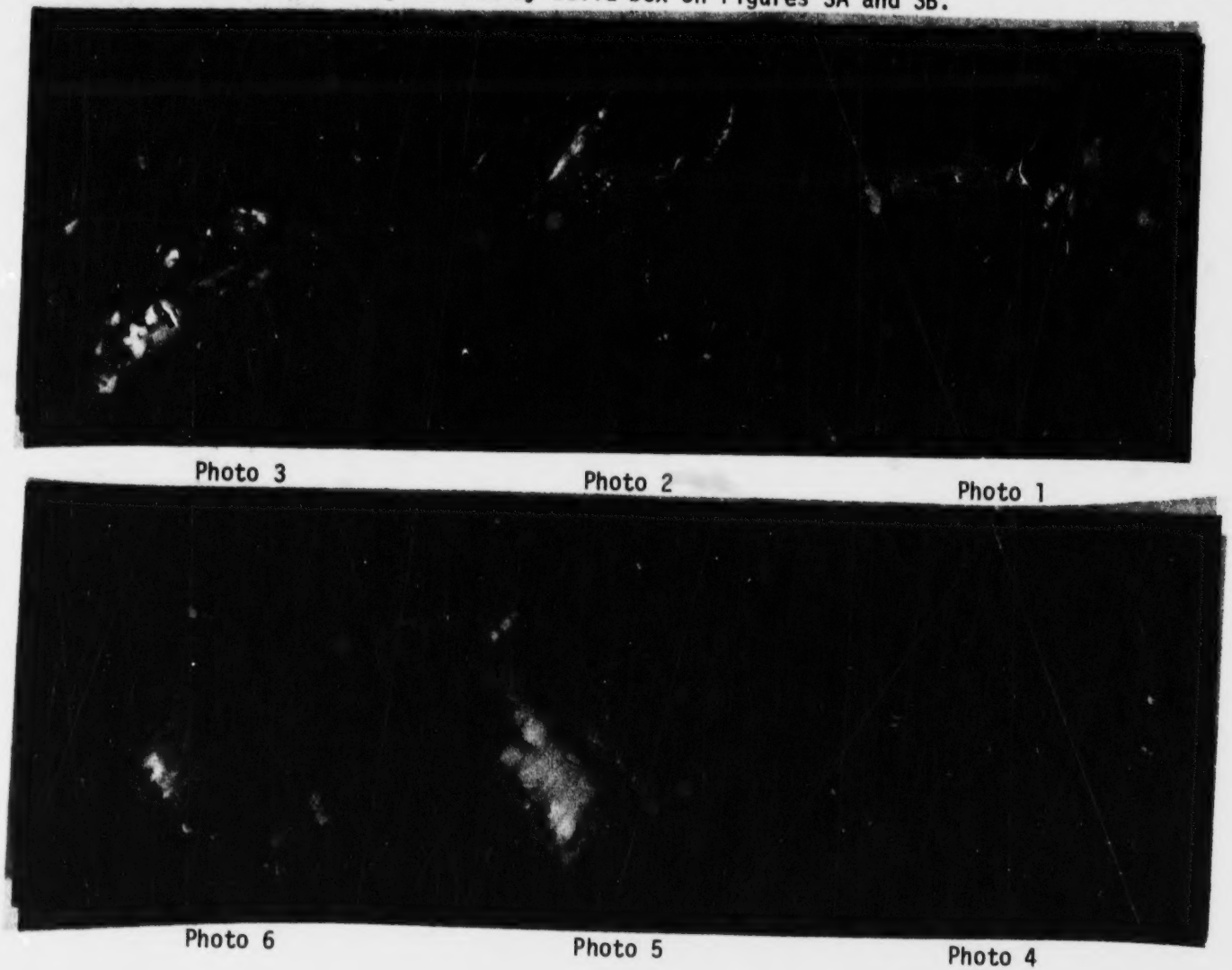


Figure 3B Example of High Level Photography

High level photography showing the impulse radar plane (circled), the flightline, and predominantly multi-year ice. Smooth first-year ice is visible along the lower and right hand sides and in the area containing the dotted line. Symbols correspond to those in Figure 3A, and boxes correspond to low level photos in Figure 3C.

Figure 3C Example of Low Level Photography.

Low level photographs showing multi-year ice surface features as seen from the impulse radar plane. Photo 1 shows ridge marked by solid box on Figures 3A and 3B.



(4) thick first-year ice was penetrated and showed a relatively flat bottom surface with a thickness of approximately 1.4m;

(5) a characteristic multiple reflection that was independent on aircraft height was observed below the surface of first year ice. This pattern was probably caused by strong returns from the flat top surface of the ice that reflected via parts of the aircraft to the antenna. This caused the signal to be delayed in time and appear later than the ice surface echo.

The impulse radar returns from multi-year ice had the following features:

(1) the top surface was not smooth, but had characteristic undulations giving an irregular ice surface echo;

(2) the ice freeboard was often distinctively greater than for first-year ice;

(3) multi-year ridges and hummocks were generally smoother than their first-year counterparts and hence gave a stronger radar return from their top surface;

(4) although multi-year ice was often penetrated by the radar signals, giving clear bottom echoes (including from bottoms of ridges and hummocks), the bottom echoes were usually sporadic or discontinuous.

(5) The aircraft reverberation was usually not pronounced.

By using the ice surface echo characteristics to distinguish first-year and multi-year ice, the impulse radar data from legs 1, 2 and 3 of Day 2 were analyzed to obtain the percentages of first-year and multi-year ice encountered along the flight-line (Table 3)

Side-Scatter Echoes

To evaluate the distribution of multi-year ice thicknesses as sensed by airborne impulse radar, the question of side reflections must be considered. It can be seen from Appendix 2 that the impulse radar antennas do not transmit or receive a narrow-beam signal. The resulting footprint (area of ice covered by the antenna pattern) can allow echoes from ice surface features lying to the side of the flight line to be received. Since these signals travel further than signals received from the ice surface at nadir, they are delayed in time and appear "below" the ice surface. This phenomenon also occurs when a good radar scatterer lies along the flight line. In this case, radar signals are received from the feature before, during, and after the aircraft passes directly over it, causing a downward hyperbolic "tail" on both sides of the feature.

In order to estimate the importance of side-scatter, a section of first-year ice was examined which showed no bottom echo, had a very flat surface, and had a ridge branching off at 10^{0} to the flight line as observed in the high level photography. Reflections from the ridge were visible "below" the ice surface when the ridge was 45 m to the side of the flight line, but their signal was weaker than typical multi-year bottom returns. Multi-year ice usually has a rougher surface than this section of first-year ice, resulting in a greater number of random side reflections. Thus any one particular side reflection will not stand out clearly. Almost all of the multi-year ice bottom returns used in the analysis were very strong and unmistakable. Therefore, in the thickness distribution the contribution from weaker side reflections is expected

to be minor.

The shape of the probability density function that we determined (Figures 4 to 6) is in itself a confirmation of the previous argument. Random side reflections misinterpreted as ice bottom features would be expected to give a distribution that peaks at the lowest time delay (i.e. 16 ns or an apparent ice thickness of 1.3 m) and fall off with increasing thickness. This is not the case, since the PDF drops off quickly for thinner ice. Therefore we have assumed that the contribution from side reflections is negligible for this study.

Ice Thickness Determination

To obtain thickness measurements from impulse radar data it is necessary to convert the time delay between the ice surface and ice bottom echoes into the distance travelled by the radar signal. However, since the velocity of radar signals at about 200 MHz travelling through various types of sea ice is variable, a velocity thought to be representative was assumed. A velocity of 1.6×10^8 m s^{-1} was used, based on results of Vant (1976) and Vant et al. (1978). This value corresponds to a dielectric constant of 3.5 (see Table 2). We believe that the probable error due to the variability in the speed of the pulse through multi-year ice would be less than $\pm$4%. Using this velocity a distance scale was drawn up to directly convert two-way travel time into multi-year ice thickness.

In evaluating the penetration ability of the impulse radar, the first goal was to determine how much of the multi-year ice was sounded, and the second aim was to see if there were favourable (or unfavourable) conditions for penetration. To achieve the first objective, the total

Table 2. Typical Electrical Properties of Ice at 200 MHz

Parameter	Air	Freshwater Ice	Multi-year Sea Ice	First-year Sea Ice
Relative dielectric constant	1.0	3.2	3.5	4.5
Signal speed ($\times 10^8$ m s^{-1})	3.00	1.68	1.60	1.4
Attenuation (dB m^{-1})	-	<<1	2-3	5-10
Brine Volume ($^o/_{oo}$)	-	0	15-20	50-100

Note: Natural sea ice exhibits a wide range of brine volumes depending on temperature and salinity. The electrical properties depend primarily on the brine volume: for increasing brine volume pulse speed decreases and attenuation increases.

length of bottom return echoes was calculated for each leg. This total was then represented as a percentage of the total distance flown over multi-year ice for that leg as determined by the ice type analysis. The combination of legs 1, 2 and 3 was also considered. To achieve the second aim, a visual examination of on the impulse radar plot and the corresponding high level photography was made to find differences between areas of penetration and areas where bottom echoes were expected but not observed. Consideration was given to various surface characteristics (floe size, surface roughness and snow cover from high level photography), ice thickness, and the estimated bottom roughness.

Only multi-year ice was considered in the thickness distribution analysis for two reasons: much of the first-year ice could not be sounded due to the 1.3 m minimum thickness imposed by the radar system; and, the more limited range of brine volumes typically found in multi-year ice probably allows a more accurate estimate of the radar velocity.

The thickness distribution of multi-year ice was obtained by determining the thickness of multi-year floes whenever they were penetrated by the impulse radar signal. As well, the horizontal extent or "length" of each bottom echo was measured, using a scale based on aircraft speed, radar scan rate, and visicorder paper speed. The horizontal scale was verified against the high level photography, and found to be accurate to $\pm 7\%$.

The speed of the aircraft put a limit of 5 m on the minimum length of ice bottom that could be distinguished accurately, and all longer sections of bottom return were divided into 5 m pieces. The thicknesses were measured to the nearest 0.1 m. Frequency distributions of the

thickness associated with each 5 m long bottom echo were drawn up for each of the three legs on Day 2 (Figure 4) as well as their combination (Figure 5).

To normalize the frequency distributions, each frequency (f) was divided by the total number of 5 m long observations for the distribution (Σf). To standardize the graphs, the thickness scale was divided by ten to give thicknesses in metres, and the probability density was multiplied by ten correspondingly to give a dimension of m^{-1}. The probability density function (PDF) sketched in Figure 5 (solid line) was drawn using points obtained by averaging in groups of four 0.1 m thicknesses, i.e. a bin size of 0.4 m. Figure 6 shows the points obtained by averaging in groups of five thicknesses -- a bin size of 0.5 m. Note that the averaging was done for this figure so that the averaged points occur on the whole and half metres; hence, the points at 1.0 and 1.5 m are not meaningful since the data go to zero at 1.3 m.

Multi-year Ice Thickness Distributions

March 17, 1979. Bin size 0.1 m.

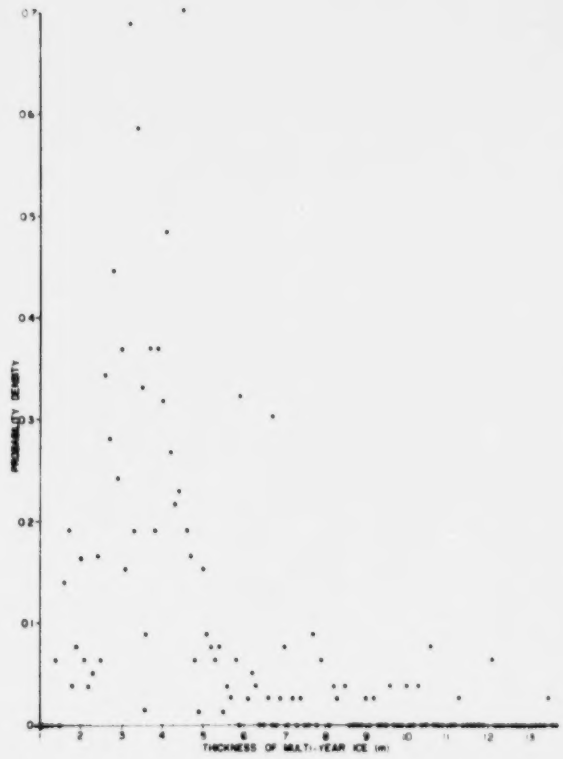


Figure 4A

Leg 1, Day 2
129.19 line km over ice
50.14 line km multi-year ice
3.92 line km of multi-year penetrated
mean = 4.08 m
median = 3.66 m

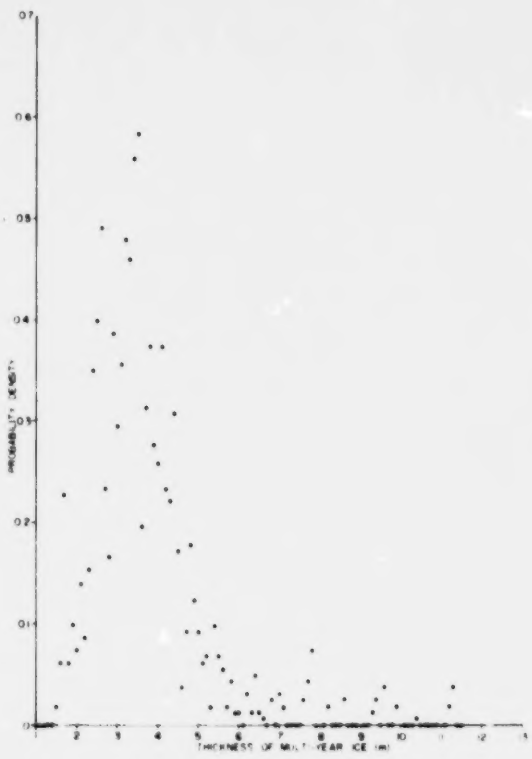


Figure 4B

Leg 2, Day 2
137.68 line km over ice
82.95 line km multi-year ice
8.15 line km multi-year penetrated
mean = 3.65
median = 3.37

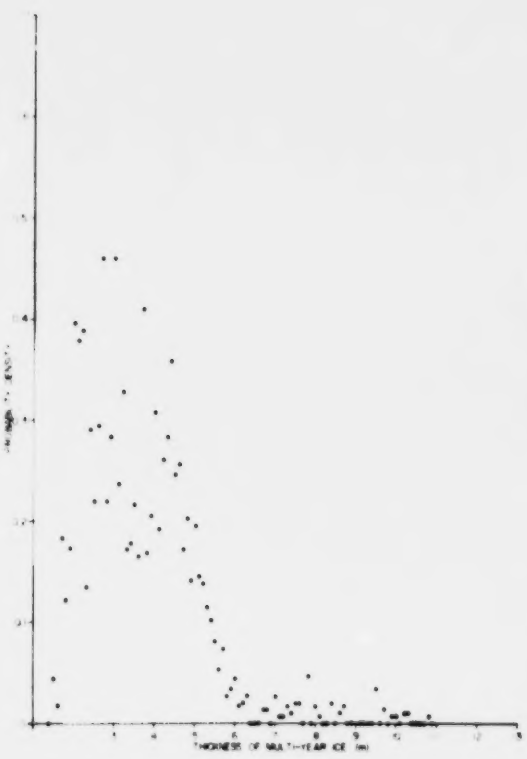


Figure 4C

Leg 3, Day 2
172.78 line km over ice
110.19 line km multi-year ice
14.77 line km of multi-year penetrated
mean = 3.64
median = 3.41

RESULTS AND DISCUSSION

Ice Type Results

An attempt was made to show the validity of the ice type determination procedure by comparing the results of analysis by impulse radar and high level photography of leg 1, Day 2 in 5 km long sections. Mr. L.G. Spedding of Esso Resources Canada had performed an ice type distribution from the high level photography (Appendix 3). Section by section comparison of the two approaches (Table 3) showed a reasonable correlation (within 10 percentage points), bearing in mind that the impulse radar samples only a line through the photographic image. The results of the radar and photograph ice type analyses of all three legs on Day 2 and their combination are presented in Table 3.

Multi-Year Ice Penetration Results

Table 3 also summarizes the amount of multi-year ice penetrated by the impulse radar for legs 1, 2, and 3, and combined. The total length of bottom from the impulse radar data on Day 2 is 26.8 km, representing 11% of the multi-year ice overflown, which was 55% of the total ice cover.

Qualitative examination of the radar plots for the effect on penetration by surface characteristics, floe size, snow cover, ice thickness, and estimated bottom roughness, indicated that none of these factors appear in themselves to limit penetration capability. Penetration through ridges was less likely than through level ice, although the shoulders of a ridge appeared to be more easily penetrated than its peak. A possible explanation is that scattering of the radar signal inside a ridge is important for some multi-year ridges. Ice thickness itself does not appear to be a limiting factor for penetration since ice from 1.3 to 13.5 m thickness

Table 3. Ice Type and Penetration Results

Day 2	Distance Covered in Analysis (km)	% First-year ice (Impulse Radar)	% Multi-year ice (Impulse Radar)	% Multi-year ice (Aerial Photography)	% Penetration of multi-year ice (Impulse Radar)	Penetration of multi-year ice (km)
Leg 1	129.2	61%	39%	43%	7.8%	3.92
Leg 2	137.7	40%	60%	67%	9.8%	8.15
Leg 3	172.8	36%	64%	66%	13.4%	14.77
Combined Legs 1, 2 and 3	439.7	45%	55%	59%	11.0%	26.84

was penetrated in this study, and all echoes were strong and clear. The effect of bottom roughness on the ability to obtain clear bottom echoes is difficult to assess. However, this factor may be important since changes in thickness by a factor two were observed on individual floes.

Pieces of ice that were not penetrated (Figure 3A) may also have significantly higher signal loss due to a greater brine volume. In level multi-year ice refrozen areas that had flooded during the summer might have higher radio-wave losses. In deformed multi-year ice inclusions of poorly consolidated ice may be present. The highly erratic nature of the radar returns clearly warrants further investigation, and particularly the ablation of ice during the summer and its re-freezing in the early autumn.

It must also be re-iterated that the radar system used was not optimal, and greater penetration has been obtained with an 80 MHz impulse radar set-up (Rossiter et al., 1980). Moreover, use of the GSSI system from a relatively fast fixed-wing aircraft flying at relatively high altitude provided limitations. Therefore the relatively low penetration rate achieved may not be typical for future operations. For example, if the radar had had a greater performance figure, it is possible that a greater penetration rate would have been observed (Figure 8). Work is underway to try to estimate what improvements can be realistically expected (Butt and Gamberg, 1980).

Multi-year Ice Thickness Distribution

The points of the probability density (Figures 4 and 5) show considerable scatter using a 0.1 m bin size. The scatter appears to be due to

under-sampling, since bin sizes of 0.4 or 0.5 m (Figures 5 and 6) give much smoother curves. Although the three legs are shown separately in Figure 4, there is no indication that they are long enough for meaningful comparisons of these data sets within themselves (although vigorous statistical tests of this assumption have not been made).

Analysis of sonar profiles of ice by Wadhams and Horne (1978) and Wadhams (1980) indicates that the thick-ice tail of the PDF is expected to fit a negative exponential. The impulse radar ice thickness PDF also appears to fit a negative exponential, as seen in Figure 7. The probability density data for ice thicker than 4.0 m was averaged over 1 m intervals and plotted on a semi-log graph. A 1 m bin was used bacause the data were very sparce beyond 8.5 m thickness. The resulting least squares fit has the form PDF (t) = 1.96 exp (-0.62 t), where t is multi-year ice thickness (m). The coefficient of correlation, $r^2 = 0.96$.

Comparison with Sonar Data

The ice thickness distribution determined by impulse radar compares well with the distribution of ice draft obtained from the USS Gurnard submarine sonar profile in the AIDJEX area of the Beaufort Sea by Wadhams (1979) and Wadhams and Horne (1978) given in Figure 6. Wadhams and Horne describe three overlapping ice thickness distributions: "an initial peak, due to thin ice in leads and polynyas; a second, broader peak due mainly to underformed first and multi-year ice; and a tail due to ice in ridges and hummocks". The impulse radar probability density function (PDF) shows only the multi-year portion of the undeformed ice peak and the deformed ice tail. It does not show the peak due to thin ice because only multi-year ice was considered.

The impulse radar PDF differs in two ways from the sonar ice draft

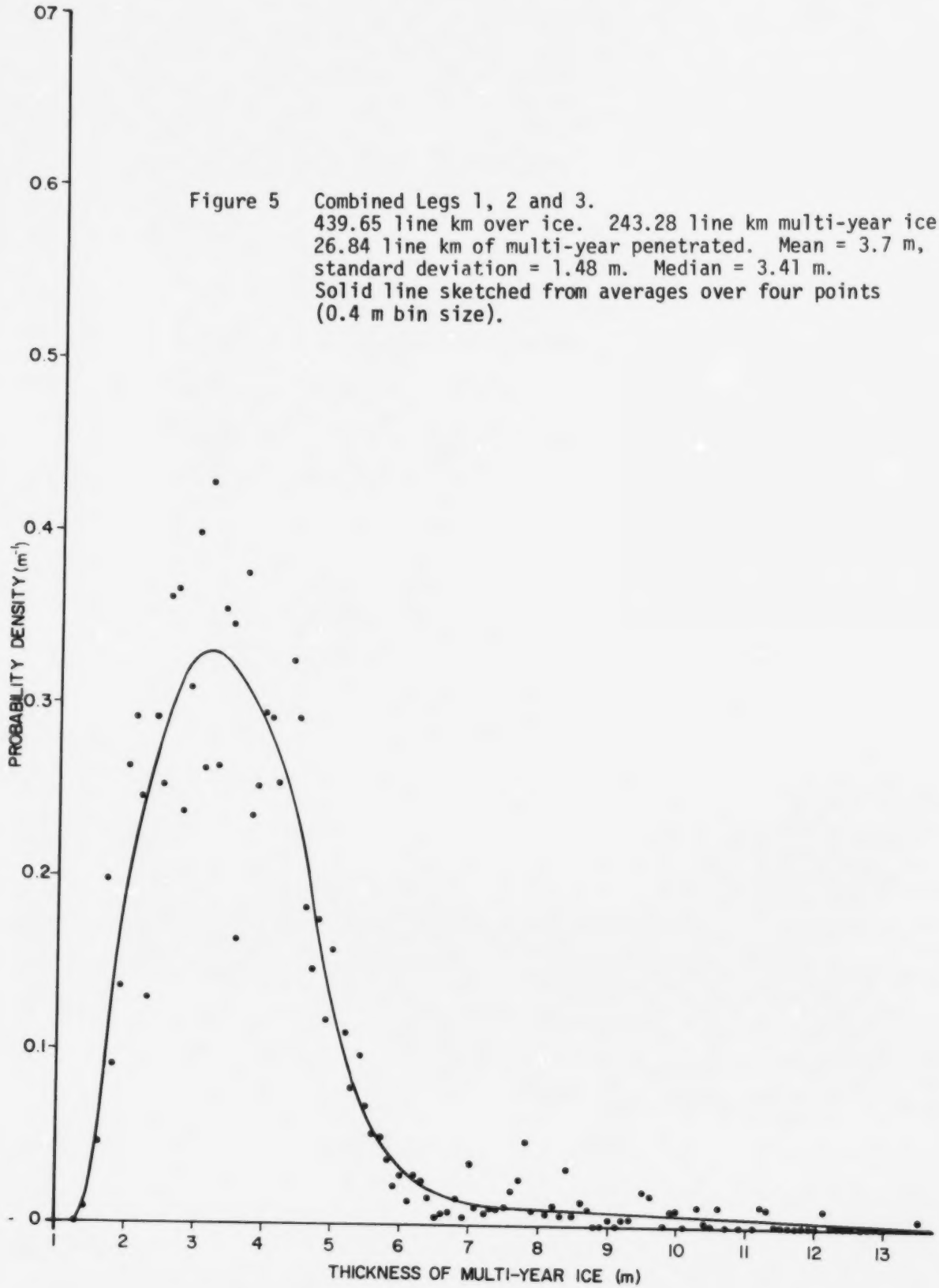


Figure 5 Combined Legs 1, 2 and 3.
439.65 line km over ice. 243.28 line km multi-year ice.
26.84 line km of multi-year penetrated. Mean = 3.7 m,
standard deviation = 1.48 m. Median = 3.41 m.
Solid line sketched from averages over four points
(0.4 m bin size).

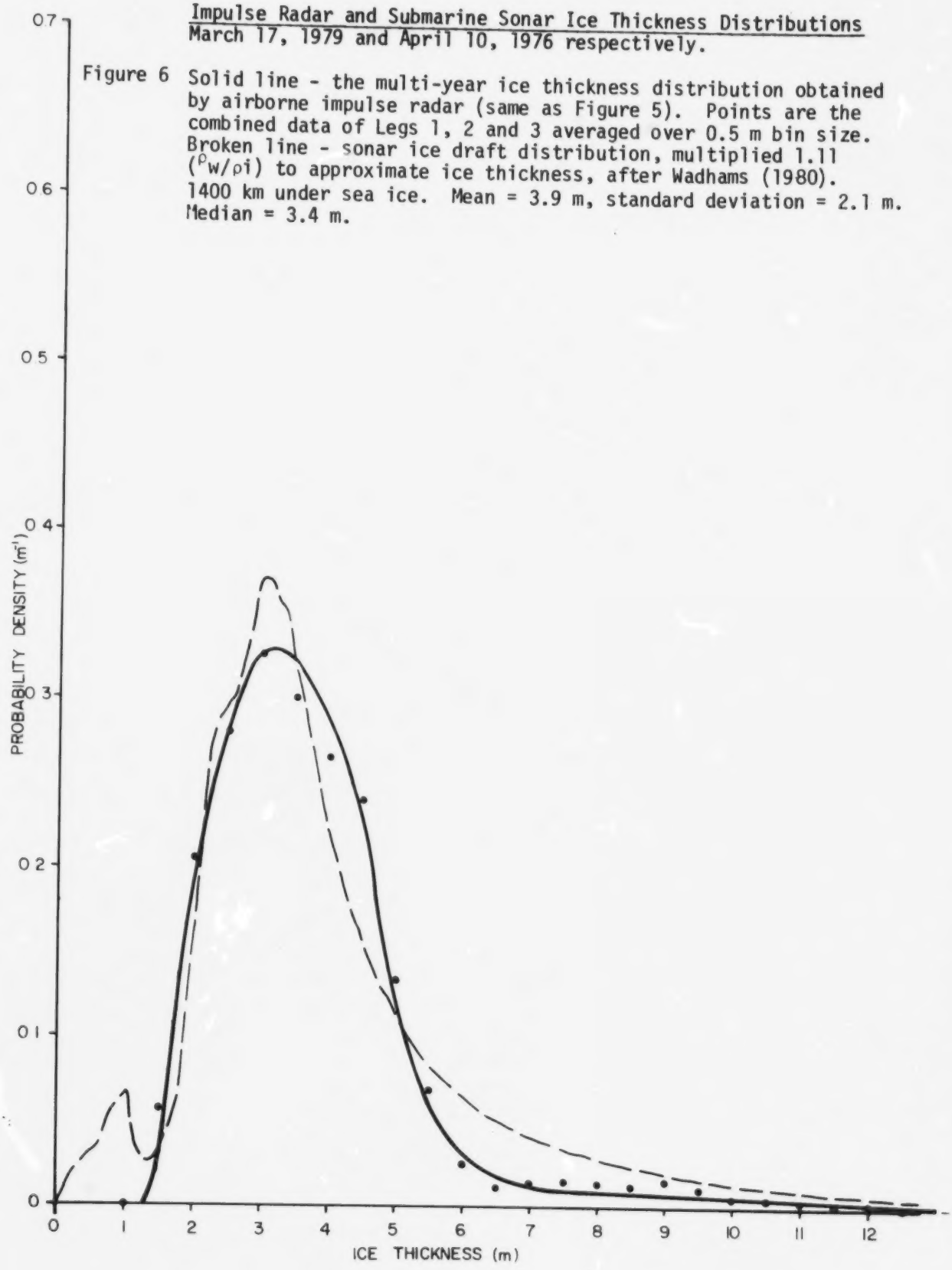


Figure 6 Solid line - the multi-year ice thickness distribution obtained by airborne impulse radar (same as Figure 5). Points are the combined data of Legs 1, 2 and 3 averaged over 0.5 m bin size. Broken line - sonar ice draft distribution, multiplied 1.11 ($\rho w/\rho i$) to approximate ice thickness, after Wadhams (1980). 1400 km under sea ice. Mean = 3.9 m, standard deviation = 2.1 m. Median = 3.4 m.

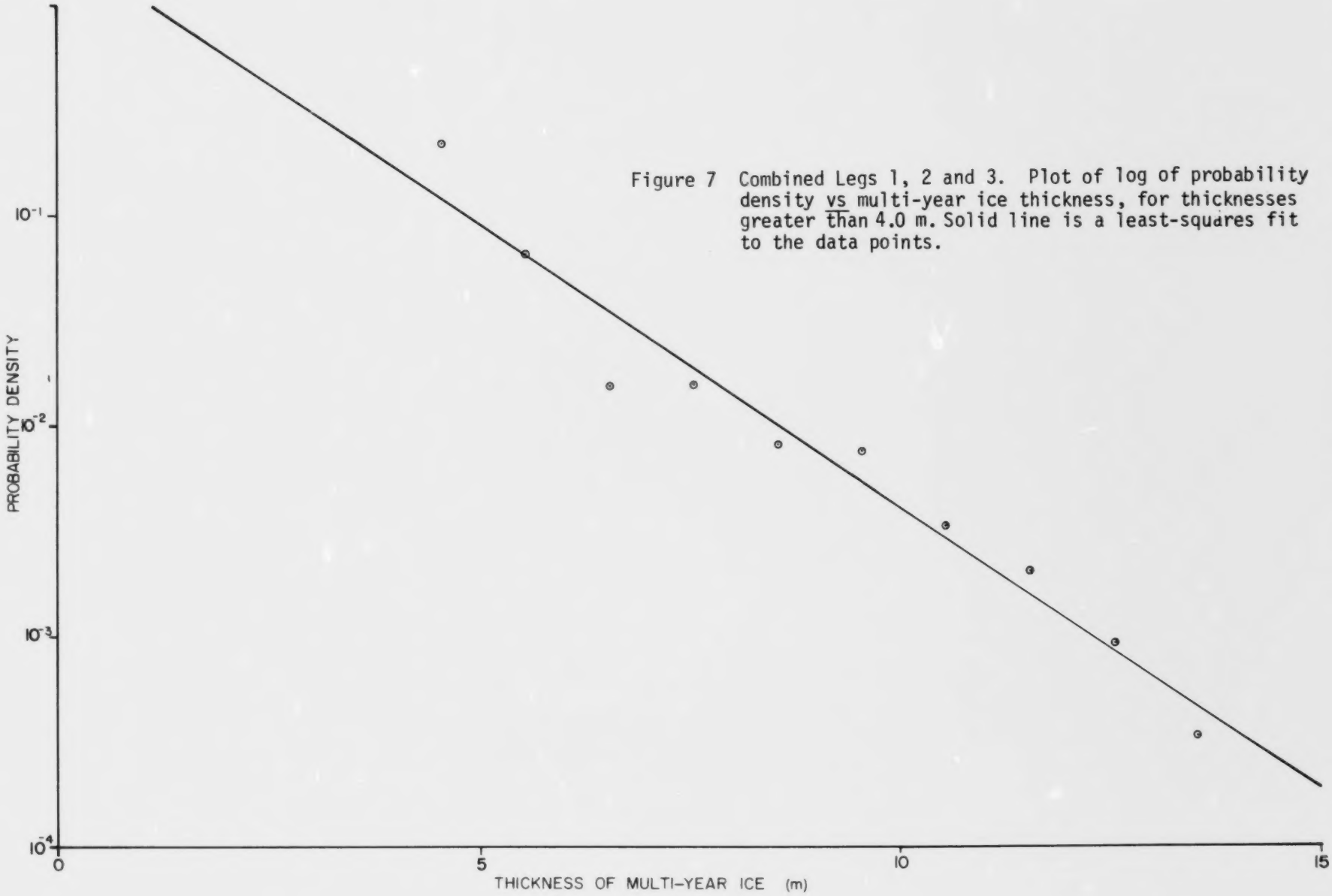


Figure 7 Combined Legs 1, 2 and 3. Plot of log of probability density vs multi-year ice thickness, for thicknesses greater than 4.0 m. Solid line is a least-squares fit to the data points.

distribution: the peak of the PDF is wider and the PDF is lower in the thick-ice tail. The wider peak may be a characteristic of multi-year ice. In the multi-year ice thickness distribution there is no contribution from deformed first-year ice because it is not penetrated by the airborne impulse radar. This deformed first-year ice in the 2 to 4 m thickness range, may contribute significantly to the sharpness of the peak in the sonar ice draft distribution. There could be several factors contributing to the lower radar PDF in the thickness range beyond 5.5 m: the actual ice thickness distribution may be different from that of the sonar study; the impulse radar may, in fact, not penetrate deformed multi-year ice as easily as level multi-year ice; the 5 m minimum echo length imposed by the speed of the aircraft may slightly favour level ice; and the impulse radar thickness distribution may be based on too small a sample.

The two ice thickness distributions are possibly different populations because they were from different areas in the Beaufort Sea (the AIDJEX area was 12 to 24^{o} west) and different years (1976 vs 1979), although the time of year differed by less than a month (April vs March). The impulse radar does not penetrate multi-year ridges easily; whereas the submarine sonar record possibly favours deep keel drafts. Smaller multi-year keels may have bottom echoes less than 5 m in horizontal extent, thus failing to contribute to the radar PDF. Quantitiative studies of the latter two possibilities have not yet been attempted.

The impulse radar data is based on total of about 27 km of bottom echoes, while the sonar data is from a 1400 km profile. Wadhams has found that 50 km lengths of submarine data are statistically similar to the complete record. Therefore the radar record may be short of

being a well-sampled data set, as well as possibly from a different ice population.

The sonar ice draft PDF of Wadhams (1980) has a coefficient for the exponent for ice drafts greater than 6 m of -0.37 for the whole track, and -0.32 for a 50 km section; for the impulse radar data it was -0.62 for ice over 6.6 m thick (r^2 = 0.93). Although Wadhams was only examing "keels", all ice thicker than 6.6 m would have been classed as a keel in his analysis. We used a 6.6 m thickness cut-off in order to compare our thickness to his draft measurements.

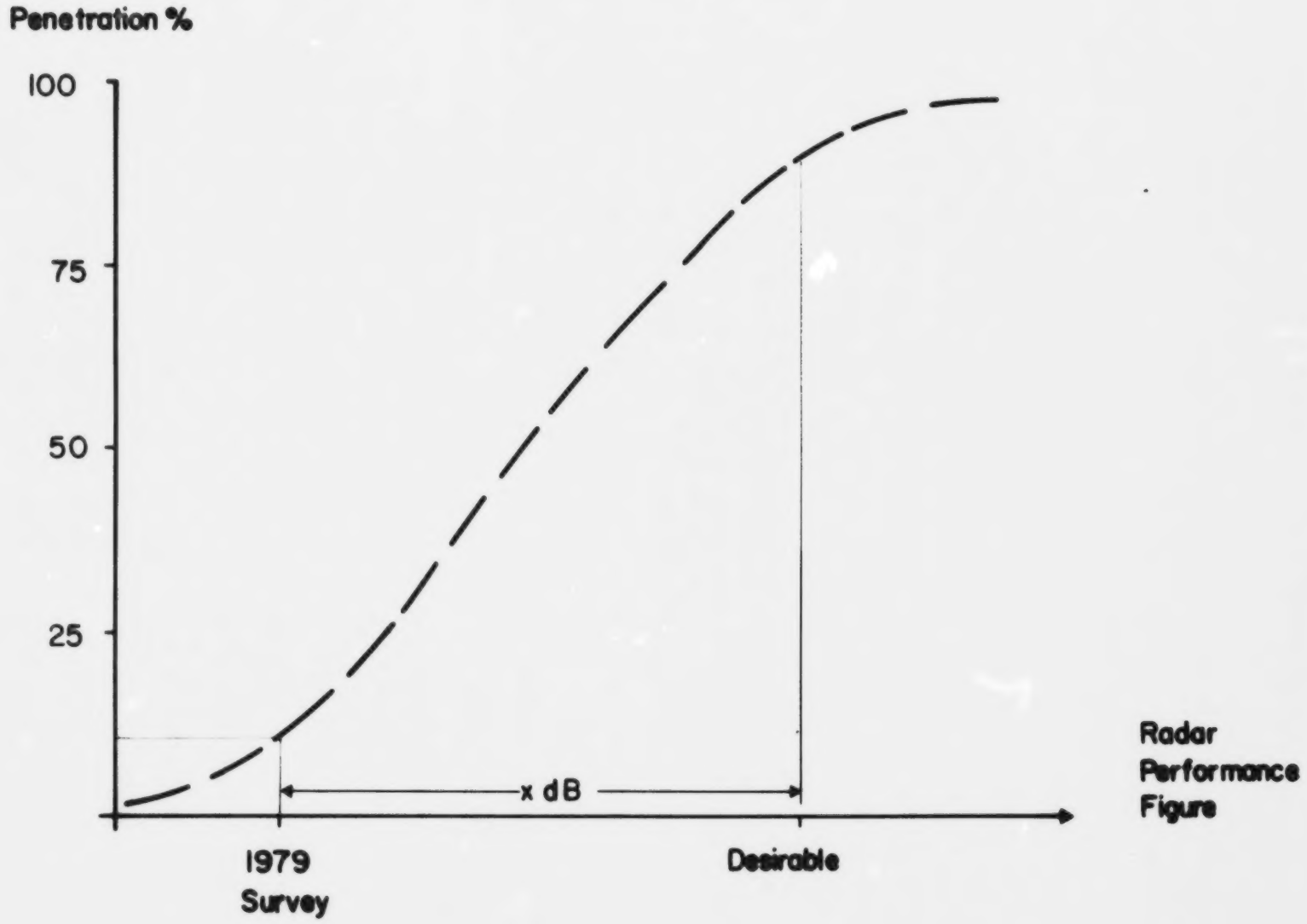
Although the radar PDF falls off by approximately exp(-0.25t) faster than the sonar keel draft, it is quite significant that both distributions do follow a negative exponential. More work is needed to determine whether the differences between the data sets are due to methodology, sampling, or different ice regimes. Recent work by Wadhams (1980) indicates that it may be possible to correct for some of the differences in methodology (narrow-beam vs wide-beam sensors and keel draft vs ice thickness, for example). If these steps are taken it could be possible to better characterize the range of possible ice thickness distributions for a given region.

CONCLUDING REMARKS

There were several novel aspects to the experiment described in this report. It was the first recorded use of impulse radar from a fixed-wing aircraft, it included a real-time print-out of the results in the aircraft, and it produced a compilation of Arctic ice thickness distribution inferred from thickness (as opposed to roughness) measurements.

The Otter installation, although experimental, was quite successful in obtaining data over long lines quickly. The use of a second Otter simultaneously collecting photographic data at high altitude was very useful in initial interpretation of the radar data. It would be possible to further refine the radar for more routine installation in a small fixed-wing aircraft, although flying height in the foreseeable future will be limited to a few hundred feet or less.

The low penetration rate of multi-year ice (11%) cannot be assumed to be the state-of-the-art. Lower frequency systems flying at lower altitude (e.g. from a helicopter) would be expected to perform better. However, it is important to estimate how much improvement in the radar itself would give a useful improvement in the acquired data. In Figure 8 a hypothetical curve of penetration rate is shown. It is quite likely that at least part of the lack of penetration is due to absorption of the signal by the ice; therefore an improvement in radar performance will offer greater penetration. However, there is no information on what improvement could be expected until something about the curve shown in Figure 8 is known. Even then there are practical limitations to the performance possible from impulse radar systems, and these limitations might only be overcome by use of novel ice sounding radars. Lower frequency systems might also be more effective in penetrating a greater



Hypothetical Sounding Success Rate.

Figure 8 - An increase in radar performance figure is likely to increase the percentage of ice sounded. The hypothetical dashed line needs to be illucidated in order to estimate how much improvement is possible using better radars.

percentage of ice, but would have decreased horizontal and vertical resolution (Rossiter, 1980).

If, however, the primary reason for lack of bottom echoes is fading due to the roughness of the ice bottom, then increased radar performance will not alter the penetration rate signficiantly. (Use of several non-harmonically related frequencies might be required). Therefore it will be important to estimate the importance of this factor; too little is presently known about multi-year ice to be able to address this question.

In spite of these limitations, airborne impulse radar appears to be a useful sea ice sensor. In this study, determination of first-year and multi-year ice types and the calçulation of a multi-year ice thickness distribution have been demonstrated. Over a 440 km line an interpreted 55% multi-year ice agreed with photographic interpretation. Distinguishing multi-year and first-year sea ice from the radar returns is based mainly on the undulating surface roughness of the multi-year ice. Eleven percent of the multi-year ice, or approximately 27 km, showed clear bottom echoes whose distribution agrees qualitatively with PDF's obtained for ice drafts from submarine sonar profiles, although it falls off more quickly at greater ice thickness. The maximum thickness penetrated was 13.5 m.

Penetration of multi-year ice is highly variable over any individual floe, and although it does not appear to be dependent on floe size, surface roughness, snow cover, ice thickness or bottom roughness, penetration of ridges is poorer. More work is needed to understand the erratic nature of these echoes. Side reflections did not appear to bias the multi-year ice thickness distribution significantly.

Further statistical work could be undertaken with this data set, in addition to further analytical comparisons to sonar and/or laser profilometer studies. Airborne impulse radar does provide an ice surface echo, similar to a laser profile, but with a much larger footprint even from low altitude. Hence it is possible, if aircraft motion is removed, to determine an ice surface profile, and from it ridge height statistics. This record is less sensitive to snow than a laser profile, since snow is essentially transparent to the radar, but impulse radar receives quite weak echoes from first-year ridges and rubble piles, which are highly effective random scatterers.

This report may represent the first Arctic sea ice thickness distribution study based on an ice thickness estimate rather than inferred from top-only and/or bottom-only profiles. Although airborne ice sounding radar is still in its developing stages, it appears to offer unique data collection possibilities, and should become a more routine operational tool as the current limitations are resolved.

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APPENDIX 1

Remote Estimation of the Properties of Sea Ice, Beaufort Sea Field Trip Report - March 1979

Remote Estimation of the Properties of Sea Ice, Beaufort Sea Field Trip Report - March 1979

James R. Rossiter

Kenneth A. Butt

This report fulfils the commitments of Phase I of Contract Number 1SU78-00347, Supply and Services Canada. The Scientific Authority is J.L. Davis, Geological Survey of Canada, Department of Energy, Mines and Resources.

Data Report

C-CORE Publication Number 79-9

June 1979

C-CORE

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ACKNOWLEDGEMENTS

This work was supported primarily under Supply and Services, Canada Contract No. 1SU78-00347. Additional financial support was received from the National Research Council, Division of Electrical Engineering; Canadian Marine Drilling, Ltd.; and Esso Resources Canada, Ltd. Generous logistic support was received from Polar Continental Shelf Project. Additional aircraft support was received from CANMAR and Esso Resources.

We are grateful for equipment that was borrowed from the U.S. Army Cold Regions Research and Engineering laboratory, Memorial University Faculty of Engineering, and the Institute of Ocean Sciences, Sidney, B.C.

We would like to thank the many people who assisted in the field, especially Jim Hodges of Okanagan Helicopters, Fred Carrothers of Borek Air Services, Barry Hough of P.C.S.P., and experimenters of the SURSAT Project who assisted with some of the field measurements. Brian Gamberg and Jan Snellen of C-CORE have been responsible for much of the data processing.

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INTRODUCTION

As more work is carried out in the Canadian Arctic during winter, there exists a greater need for the ability to make remote estimates of the physical properties of sea ice. The critical properties are the thickness and strength of ice, whether it be for operations on the ice surface, or movement of ice-breaking vessels. Although progress has been made in recent years in the observation and classification of sea ice using remote sensors, little success has been achieved in remote measurement of ice thickness and strength. This ability is particularly important because of the high variability and dynamic nature of sea ice and the increased industrial activity in Canada's North.

In spite of this lack of success, there is promise of being able to sound sea ice using radio waves in or near the VHF band. At least three instruments are actively being developed in Canada which have possible application to the remote determination of sea ice thickness:

(1) Impulse radar systems, using broad band pulses in the 50 to 500 MHz frequency band, are being used routinely in the Arctic from surface vehicles. Active research work on sea ice is being pursued using these systems both at the Cold Regions Research and Engineering Laboratory in the U.S.A and at C-CORE. In addition, the Geological Survey of Canada, Electrical Methods Section, has had extensive experience with these systems, particularly for studies of permafrost and soil moisture.

(2) The National Research Council, Division of Electrical Engineering, is building a pulsed 10 MHz system for ice sounding from a helicopter. The phases of three harmonics of the pulse repetition

frequency (1.25 MHz) are measured. A preliminary field prototype of this system was tested in March 1979 as part of this field trip.

(3) Transport Canada, Research and Development Centre, Montreal, has let a contract to MPB Technologies, Inc., Montreal, to build an airborne ice thickness sensor. This system will use synthetic pulses near 100 MHz, plus an impulse radar. Initial prototypes are currently under construction.

During 1978, a need was recognized for more effective co-ordination of research efforts in Canada. With firm financial support from the National Research Council, Canadian Marine Drilling Ltd., Esso Resources Canada Ltd., and the Canadian Government (Department of Supply and Services), C-CORE mounted a joint government-industry-university field program in the Beaufort Sea during March 1979. The site was chosen to coincide in time and place with the SURSAT Project, which involved a number of sea ice studies including a number of remote sensing overflights.

Subsequent to this trip, an additional grant from NORDCO Ltd. allowed further studies of the ice on and near Lake Melville, Labrador in April. This data set, collected over ice with lower salinity than that in the Beaufort Sea, complements the Arctic results, and will be described in a separate report.

This report summarizes the participation by the various groups involved in the Beaufort Sea work, and the field data that were collected. There has been no serious attempt to interpret the data at this time, although some preliminary results are presented.

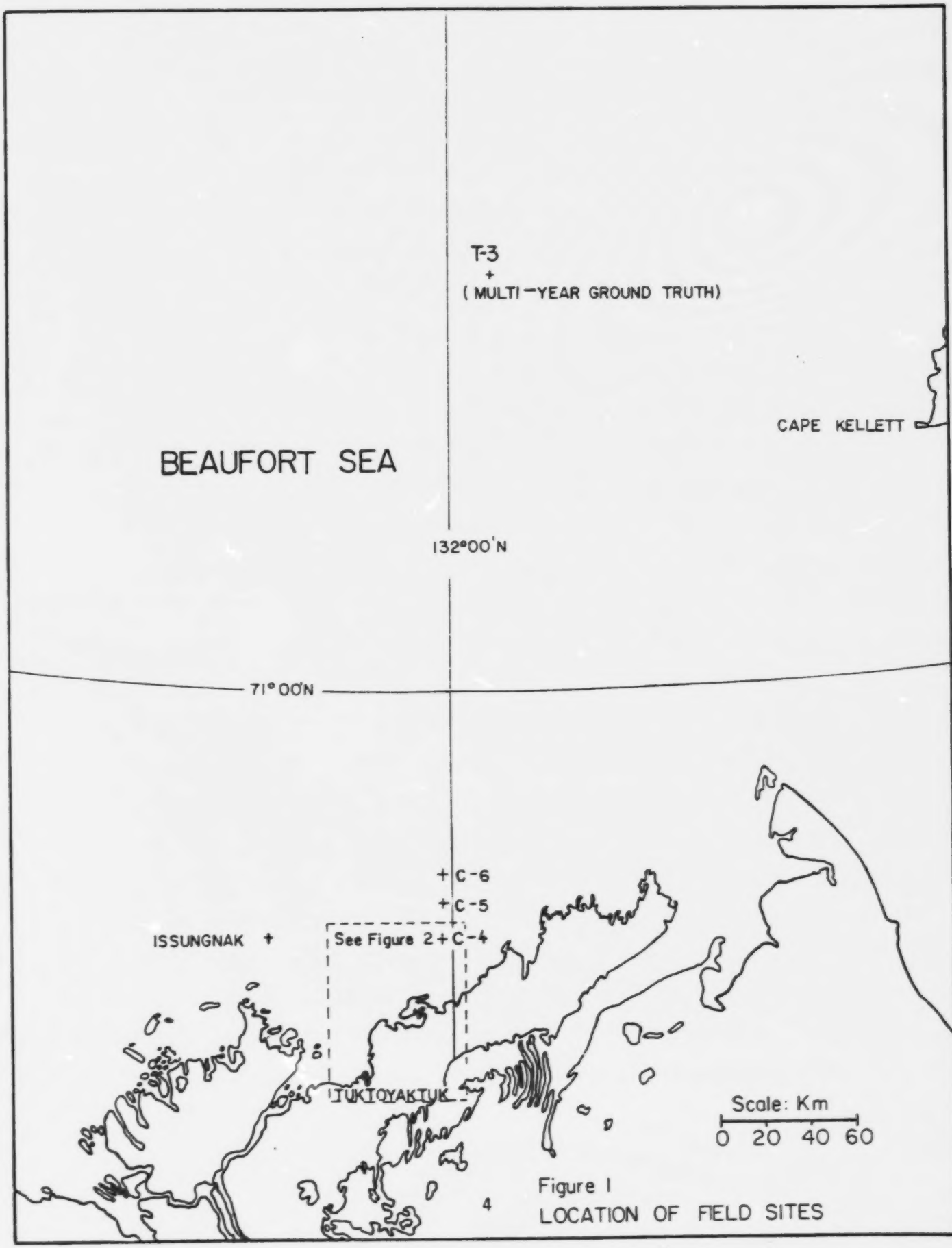


Figure 1
LOCATION OF FIELD SITES

FIELD PROGRAM

The main objective of this experiment was to collect data required for construction and design of an operational radar system to estimate the thickness and strength of sea ice from an airborne platform. Emphasis was placed on increasing our knowledge and understanding of ice conditions, particularly the *in situ* electrical properties of sea ice. A more detailed list of objectives is outlined in Table 1.

The field program operated out of the Polar Continental Shelf Project base camp at Tuktoyaktuk, N.W.T., with the first people arriving on March 2, and the last leaving on April 2. A list of agencies and personnel involved in the program is given in Table 2. The main pieces of equipment used are listed in Tables 3 and 4. A description of the sites and a summary of the data as collected are presented in Table 5, and the positions of the sites are shown in Figures 1 and 2.

The local sites, all of which were within a 75 km radius of Tuk, became designated as C-1, C-2, C-3 and C-4. The "C" prefix was used to prevent confusion between C-CORE sites and those numbered by other research groups, although several sites were the same in order to take advantage of each other's ground truthing and overflight information.

An area of multi-year ice, north of the shear zone, approximately 320 km north of Tuk and a few km south of Ice Island T-3, was studied by both C-CORE and SURSAT. Another area of interest was the ice rubble field at Issungnak, located approximately 75 km northwest of Tuk. Since the nature of this ice field restricted most conventional forms of ground truthing, only airborne data were collected by C-CORE.

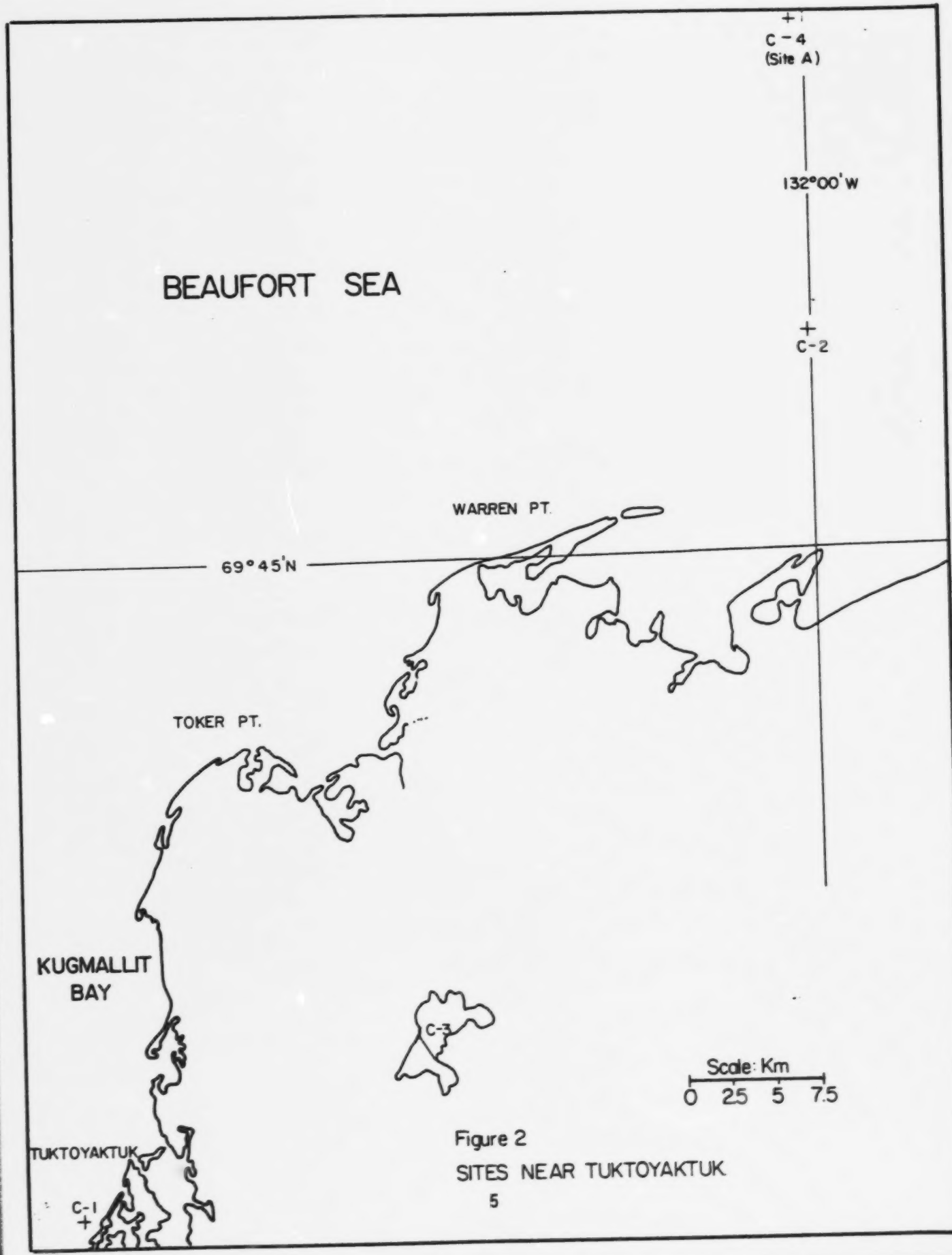


Figure 2
SITES NEAR TUKTOYAKTUK

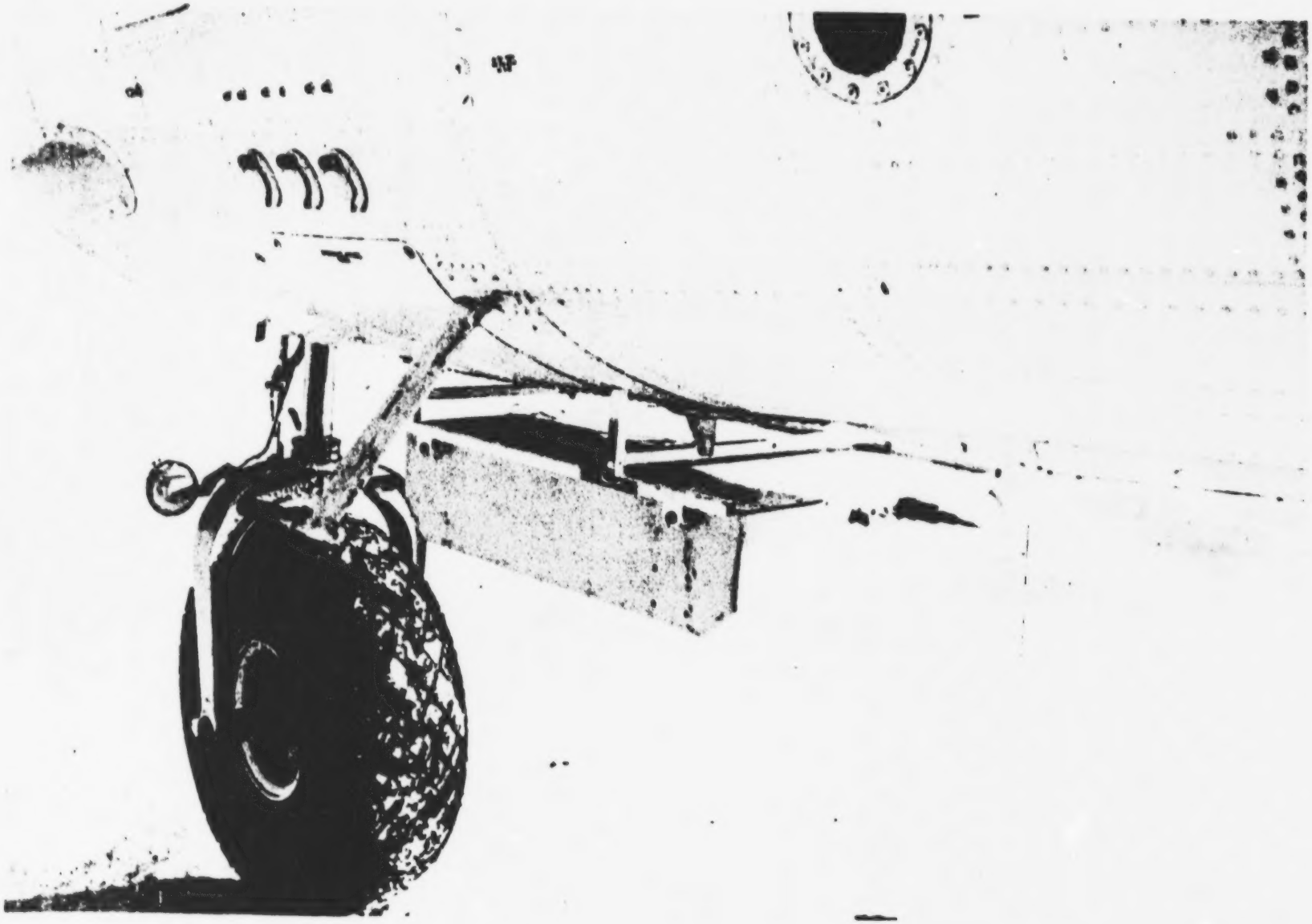


Figure 3 Impulse radar antenna, 300 MHz centre-frequency, mounted under a de Havilland Twin Otter directly aft of the nose wheel. This installation was the first reported use of impulse radar from a fixed-wing aircraft.

PRELIMINARY RESULTS

Some of the highlights of the field program are presented in this section. We have attempted to report what appear, at this time, to be the more important findings, but of course any conclusions are preliminary.

This field trip included the first use of impulse radar from a fixed-wing aircraft platform, a de Havilland Twin Otter (see Figure 3). Although the installation was successful, it must be regarded as experimental. Power was supplied from an on-board 110 VAC gasoline generator rather than from the aircraft supply. Interference was found between the radar and an Air Traffic Control transponder beacon mounted as part of the aircraft's instrumentation package (it was turned off during impulse radar data collection).

As a part of the Otter installation, a Honeywell grey-level visicorder was used to produce hard-copy output of the impulse radar results with about one minute delay. This facility is invaluable in ascertaining whether the radar is operating effectively, and to pick out important features without returning to base.

The aircraft was flown at 100 to 140 knots airspeed (50 to 70 m s^{-1}). The scan repetition rate of the impulse radar (51.2 scans/second) is probably not fast enough for routine fixed-wing use, since only a single scan of data was collected per metre of forward movement. The ice characteristics can change substantially in this distance, giving significant differences in returned signal from scan to scan, even over relatively uniform ice.

Data were collected at altitudes from 100 to 300 feet above sea level (30 to 100 m). There were noticeable differences between results from lower and higher level operation, caused primarily by the larger

footprint of the radar at higher altitude. The antenna of the radar is a modified dipole, and the footprint size is the same order of magnitude as the flying height. It was found reasonably easy operationally to fly for several hours at 30 m elevation.

Photography was taken along with the radar data, both at low level from the aircraft with the impulse radar and, over some of the traverse, from a second Otter flying at 8000 feet (approximately 2440 m). Complete photographic coverage was not possible using the lower aircraft because of the proximity of the ice, but use of a second higher aircraft appears to have been successful except when a cloud layer came between the two aircraft.

The major target of the Otter overflights was multi-year ice (see Figure 4), which was over 200 nautical miles (320 km) from Tuk. Only the 300 MHz centre frequency antenna system (Figure 3) was used for the fixed-wing work in order to facilitate mounting the impulse radar. Reliable bottom echoes were received from many of the multi-year floes overflown, but we have not yet determined whether or not these data can be used to infer multi-year ice thickness distributions. This problem is of considerable importance to industrial installations, which might be designed to withstand first-year ice but would have to be moved to avoid multi-year ice.

One of the features of interest in the Beaufort Sea program was the opportunity to study Ice Island T-3. It is currently approximately 11 by 5 km in size, and several passes were made over it with the impulse radar. There was a very clear bottom echo since the ice is of glacial origin with negligible salinity. The thickness appears to be 10 to 30 m, with some underside relief, as shown in Figure 4.

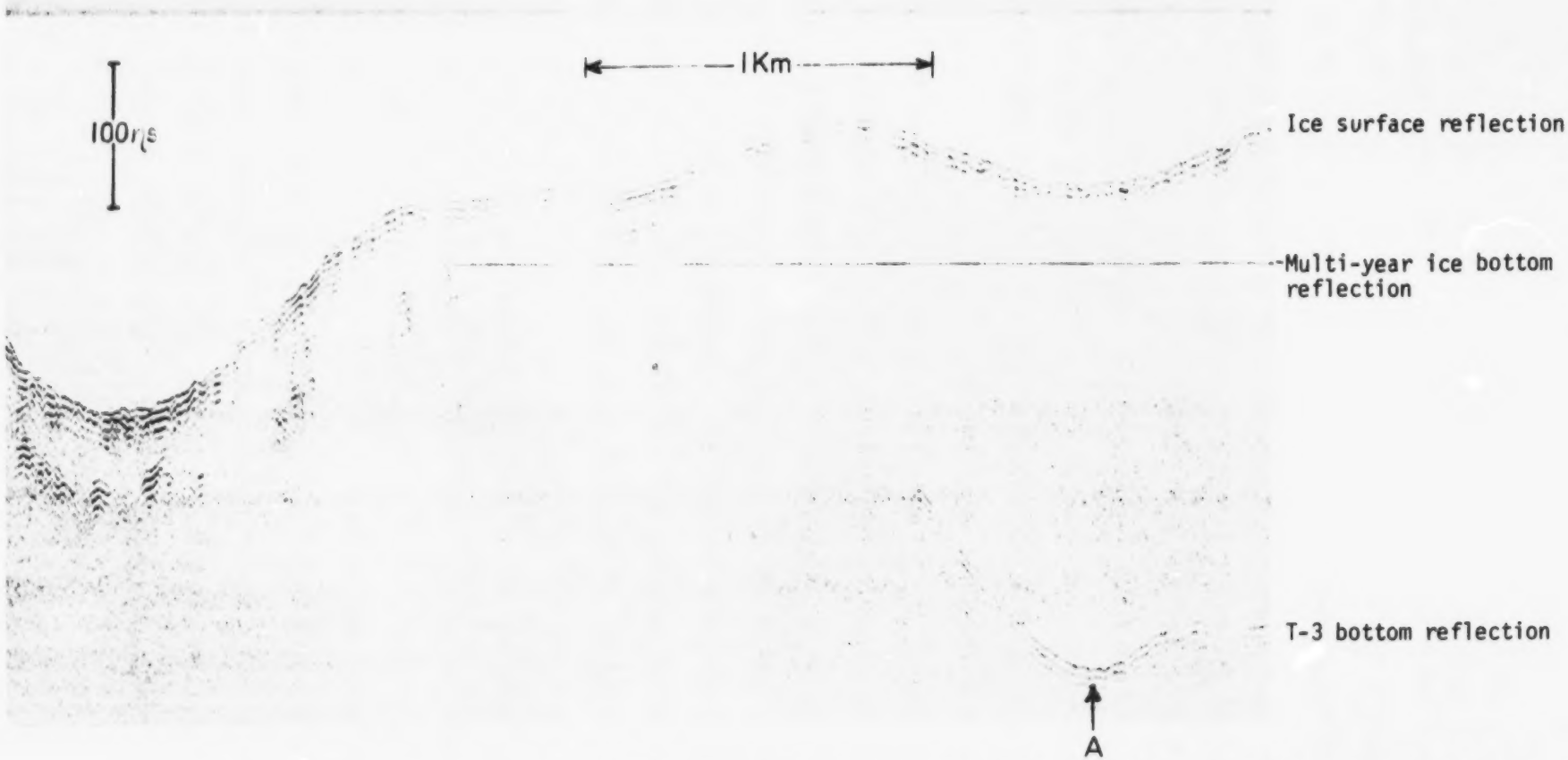


Figure 4. Airborne ice thickness profiling using impulse radar (300 MHz) in the Beaufort Sea in March 1979 from a de Havilland Twin Otter at 250 feet (80 m) elevation and 140 knots (70 $m\,s^{-1}$) airspeed. The aircraft travelled from right to left; the echo delay time increases down the page. This record shows a corner of Ice Island T-3 and some multi-year ice floes. The thickness of T-3 at point "A" is calculated to be 26 m.

One of the major aims of the project was to fly the impulse radar over as many different ice types as possible in the Beaufort Sea area, and to collect adequate surface truth data, including cores, for detailed analysis. It was possible to fly over freshwater ponds, brackish ice in the Mackenzie Delta, first-year ice (landfast and in the shear zone), multi-year ice, pack ice floes, ridges, and a large rubble field. Impulse radar was flown over many of these areas at several altitudes and using two different centre frequencies of about 300 and 80 MHz (see Figures 4 and 5). Detailed voice notes were made during each overflight describing ice conditions under the aircraft.

The nature of the returned signal appears to vary from ice type to ice type, and a major part of the data analysis will concentrate on understanding how these characteristics depend on the physical properties of the ice. Penetration is limited in more saline first-year ice, particularly at higher frequencies. Although this result was fully expected based on previous work, it will be important to quantify the signal attenuation. It should be noted that temperatures in the area had been quite warm until March, and the first-year ice, which is usually about 2 m thick, was rarely more than 1.3 m thick.

A region of ice with anisotropic radar returns was studied in detail. Initial results confirm that the electrical anisotropy is related to the azimuthal orientation of horizontal c-axes. However, the crystals were not uniformly aligned, even over distances of tens of metres. Under-ice current measurements were made, giving speeds of less than 8 cm s^{-1}. This result suggests that if the crystal alignment is caused by sub-ice currents, the currents need not be very large. Electrical

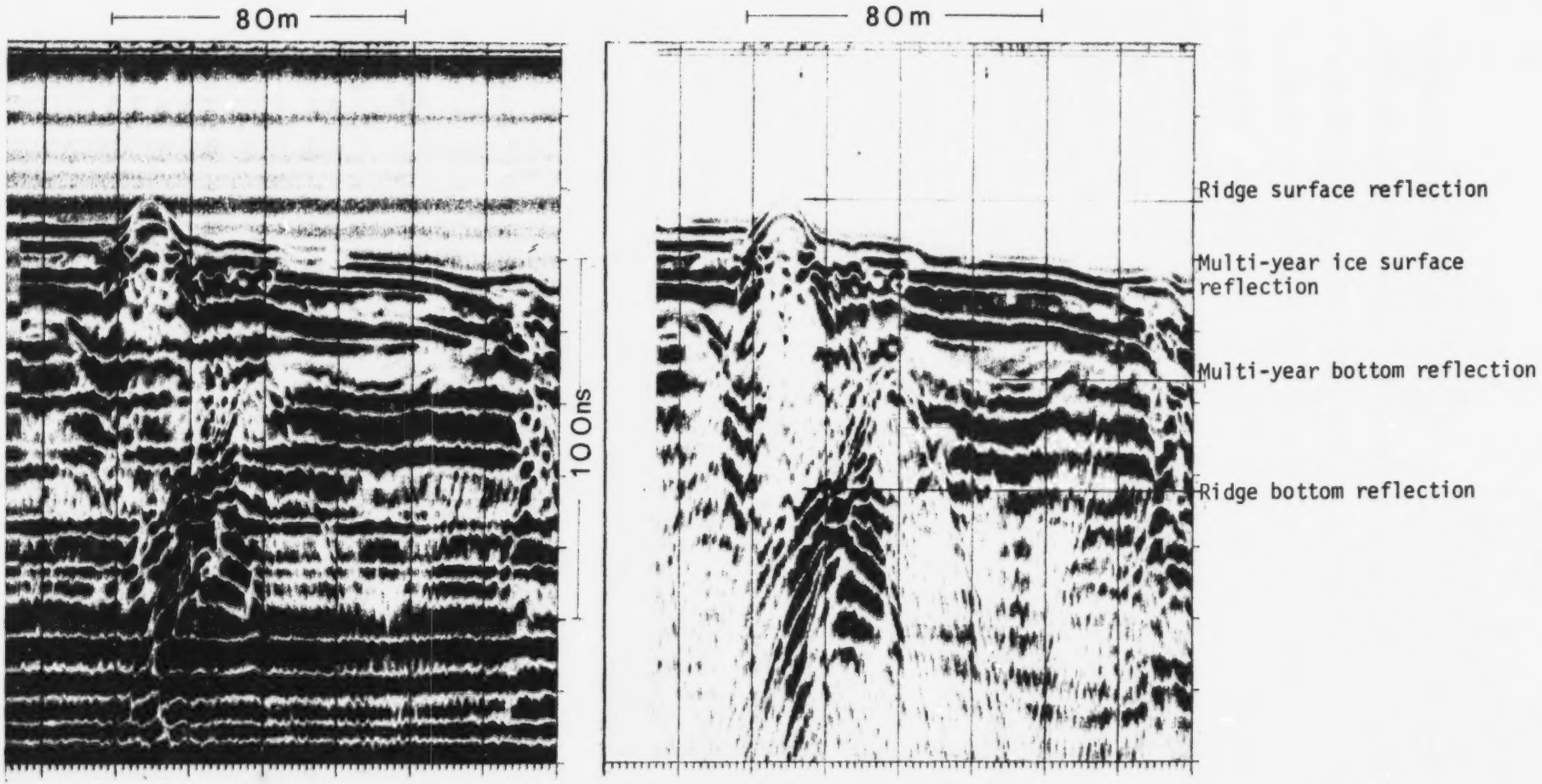


Figure 5(a)

5(b)

Airborne ice thickness profiling using impulse radar (80 MHz) in the Beaufort Sea in March 1979 from a Bell 205 helicopter at 100 feet (30 m) elevation and 20 knots ($10\,m\,s^{-1}$) airspeed. Figure (a) shows raw data after digitization; in (b) the systematic background noise has been subtracted. The ridge shown has a calculated thickness of 6 m, assuming a dielectric constant of 4 for the multi-year ice.

property measurements in two horizontal directions were made *in situ* at the same site to help understand the anisotropy in the radar returns. Measurements of the electrical properties of sea ice *in situ* using vertically polarized fields were made, possibly for the first time.

At each major site cores were taken for analysis of the density, salinity, and crystal structure. In addition, a continuously recording thermistor probe was installed for most of the month in the fast ice at the southern end of the 132°W line (site C-2). This device gave a complete temperature profile of the ice at that location, and indicated ice growth over the period. By combining the salinity and temperature records, it will be possible to calculate the brine volume of the first-year ice.

The degree of roughness of the top surface of the ice has a significant effect on the airborne impulse radar return. The radar illuminates a relatively large footprint, and the return from the ice surface is a combination of a number of interfering echoes when the ice is broken up by ridges or rubble. Therefore it is not possible to use the strength of the surface echo to obtain a measure of the electrical properties of underlying ice, as had been postulated earlier. However, it may be useful to use impulse radar to determine surface roughness properties, since the wavelengths used (1 to 4 m) are longer than those used by most conventional radars. Large ridges show up as peaks in the surface return (Figure 5) and newly refrozen leads show up clearly because of their smoothness. Both of these features can be easily picked from the data record for ice-type distribution analysis.

From a hardware point of view, more work is needed in operational

mounting of impulse radar antennas under aircraft. Microwave absorbing material placed between the antenna and aircraft (see Figure 6) reduced antenna ringing, and the newly developed shielded antenna (Figure 3) was easy to use. Improvements made in the performance figure of the impulse radar seemed successful, but the modifications introduced systematic noise into the record. The majority of this noise should be easily removable by background subtraction (Figure 5b).

Figure 6 A pair of 80 MHz centre-frequency impulse radar antennas mounted co-linearly and fitted with Eccosorb microwave absorbing material on top. This package was slung under a Bell 205 helicopter for airborne measurements. The absorbing material decreases ringing caused by the proximity of the aircraft to the antennas.

CONCLUSIONS

The field work undertaken in March 1979 in the Beaufort Sea was successful in bringing together the groups that are actively developing remote ice thickness sensing devices in Canada. Although, as always, there were equipment failures under the harsh winter conditions, at least some samples of each type of data hoped for were collected. It is expected that they will complement data sets collected by other investigators within the SURSAT Project.

At present the major thrust at C-CORE is to organize the various types of data into a format that can be readily used by a number of different people. It will be essential to relate airborne results (both radar and photography) with the various types of surface truthing (see Appendix I). Most of the analogue tapes are being digitized for quantitative computer analysis of the results. A workshop to discuss preliminary results, and to set the direction for future efforts in the problem of remote sea ice thickness measurement, will be held in St. John's on September 25 and 26, 1979 (see Appendix II).

Table 1. Arctic Field Work Objectives - Beaufort Sea, March 1979

Airborne impulse radar from Bell 205 helicopter:

- survey runs over first-year and multi-year ice, ridges, rubble fields
- 80 and 300 MHz centre frequencies
- monostatic and bistatic operation
- various altitudes 10 to 100 m ASL
- simultaneous aerial photography.

Detailed surface studies about five sites (co-ordinated with SURSAT Project):

- detailed physical properties studies and analysis of cores (thickness, salinity, density)
- temperature profiles through the ice
- wide-angle reflection and refraction studies of electrical properties
- effect of orientation of crystal axes on radar return - 80, 300, 400 MHz
- HF electrical properties using capacitive network (National Research Council)
- time-domain reflectometry and borehole radar (Geological Survey of Canada)
- detailed studies of crystallographic anisotropy of sea ice and measurement of sub-ice oceanographic currents (Scott Polar Research Institute)
- crystallographic studies (NORDCO, Ltd.).

In addition, airborne impulse radar data, along with stereo aerial photography, were collected for CANMAR Ltd. and Esso Resources Canada Ltd. using two de Havilland Twin Otters.

Table 2. Agencies and Personnel Involved in Beaufort Sea Field Program, March 1979

Person	Title	Dates in Field	Main Experiment
Centre for Cold Ocean Resources Engineering:			
Jamie Rossiter	Principal Investigator	Mar. 5-19	Airborne impulse radar
Ken Butt	Electrical Engineer	Mar. 8-26	Impulse radar
Terry Ridings	Field Technician	Mar. 2-28	Airborne photography; temperature probe
Wayne Mercer	Student Assistant	Mar. 2-16	Impulse radar
Treve Bonser	Student Assistant	Mar. 8-28	Ice properties
Scott Polar Research Institute:			
Pat Langhorne	Research Assistant	Mar. 2-Apr. 2	Ice anisotropy and crystallography; current measurements
Newfoundland Oceans Research & Development Corporation, Ltd.:			
Tim Kelliher	Ice Physicist	Mar. 9-28	Ice crystallography
National Research Council:			
Fred Hunt	Senior Research Officer	Mar. 9-23	NRC radar; capacitive measurements
Gary Gibson	Technician	Mar. 9-23	NRC radar; capacitive measurements
Geological Survey of Canada;			
Les Davis	Physical Scientist	Mar. 16-26	Time-domain reflectometry; borehole radar
John Riley	Student Assistant	Mar. 16-26	Time-domain reflectometry; borehole radar
MPB Technologies, Inc.:			
Brian Gibbs	Engineer	Mar. 22-26	Observer

In addition, the following people assisted directly with the industry-related program:

Bryan Mercer, Canadian Marine Drilling, Ltd. - Airborne impulse radar
Geoff Spedding, Esso Resources Canada, Ltd. - Aerial photography

Table 3. Equipment Used in Beaufort Sea Program, March 1979

C-CORE impulse radar:

- Geophysical Survey Systems, Inc. System SIR-7 with following transducers:

- Model 3103	400 MHz centre frequency	transmitter (Tx)/antenna
- Model 3103	400 MHz centre frequency	receiver (Rx)/antenna
- Model 3105A	300 MHz centre frequency	shielded antenna pair (Tx/Rx)
- Model 3112	80 MHz centre frequency	two identical antennas for either monostatic or bistatic operation
	80 MHz centre frequency	two identical resistively loaded dipole antennas for either monostatic or bistatic operation (C-CORE fabrication)

80 MHz electronics:

- Model 705 DAX transmitter/receiver with amplifier
- Model 705D transmitter (C-CORE modified to increase receiver sensitivity)
- Model 765 transmitter

- C-CORE auxiliary control box with two-channel cassette tape voice note facility
- Racal Store 4D 4-channel analogue FM and/or direct instrumentation tape recorder
- Honeywell 1856A visicorder and 1219 dry-silver paper processor

More detailed specifications of the C-CORE radar are given in Table 4.

Low-level aerial photography:

- 2 Hasselblad Model EL500 70 mm cameras with 40 mm or 80 mm lens and Model 500 150 ft. (750 exposure) film back

cont'd...

Table 3 Equipment Used (cont'd)

Temperature:

- 16 channel thermistor probe for ice temperature, surface to 2 m, +5°C to -50°C; plus 16 channel thermistor probe for temperatures near ice-water interface at 2 cm intervals, 0°C to -10°C (C-CORE fabrication)

- Rustrak Model 388 2-channel chart recorder

- 25 channel, 2.5 meter thermistor probe, manually sampled and recorded (C-CORE fabrication)

Current measurement:

- Propellor current meter, A. Ott No. 72472

- Electromagnetic flow meter, Institute of Oceanographic Sciences, England, Mark II

- Inductive flow meter, Cushing Model 611P-A

Ice Coring/analysis:

- 3 inch SIPRE corer with extensions

- CRREL ice thickness kit

- Electronic Instruments Ltd., Model MC-1 MK-V conductivity meter

- LEITZ sledge microtome

- Rigsby universal stage

NRC equipment:

- HF pulsed radar with transmitted PRF of 1.25 MHz and received at 3 harmonics around 10 MHz (NRC prototype)

- Wayne-Kerr Type B 801 VHF Admittance Bridge plus signal generator and detector

- Capacitive probes 30 cm and 100 cm, 1½ inch diameter (NRC fabrication)

GSC equipment:

- Tektronix Model 7S12 sampling TDR oscilloscope plus 85 cm probes

- Borehole impulse radar, plus probes for 80, 200, and 400 MHz (GSC fabrication)

Site Location:

- Orion Electronics Model O.S.T. Transmitter buoys plus Model R-8 direction finding receiver.

Table 4. C-CORE's Impulse Radar System Specifications

	GSSI 3112	GSSI 3103	C-CORE
Centre Frequency (MHz):	80	400	80
Approximate Bandwidth (MHz):	40-160	200-400	40-160
Approximate Pulse Length (ns):	10-20	3-5	∿20
Antenna Size (cm):	135 x 84 x 36	53 x 30 x 13	140 x 70 x 25
Antenna Deployment:	Bistatic or transceiver	Bistatic	Bistatic or transceiver

Antenna Type: GSSI antennas are resistively-loaded folded dipoles on a curved plane. The C-CORE antennas (new versions under development) are not folded and are on a flat plane.

Peak Power: 53/67 watts into 200Ω with GSSI model 765/705 DAX transmitters.

Performance Figure: ∿70 dB

Pulse Repetition Frequency: 51.2 KHz

Scan Rate: 3.2 to 51.2 scans/second, adjustable in steps of X2

Range Window: 25 to 5,000 ns, fully adjustable

Recording: Racal Store-4 and Store-4D analogue instrumentation tape recorders with FM and/or direct capability; 15/16 to 60 i.p.s.

C-CORE auxiliary control box: two-channel cassette tape voice note facility; dual channel Hasselblad 70 mm camera control plus step - adjustable intervalometer (1 to 100 sec.)

Display: EPC 2208 grey scale graphic recorder

Operation: Surface - sled mounted
- profile or wide angle measurements

Airborne - helicopter (Bell 205, 206, 206L)
- fixed-wing (de Havilland Twin Otter)

Power Requirements: control module - 15 watts at 10-30 VDC or 110 VAC
Racal tape recorder - 60 watts at 12-30 VDC or 110 VAC
EPC graphic recorder - 300 watts at 110 VAC
Auxiliary control box (with cameras) - 20 watts (average); 90 watts (peak) at 16-28 VDC; optional 110 VAC for record only

Data processing: HP5451B Fourier Analyzer system including ANAC 911 grey scale digital plotter (at Memorial University)

Note: Additional impulse radar equipment, listed in Table 3, was leased specifically for March 1979 Beaufort Sea field program.

Table 5. Site Locations and Data Collected Beaufort Sea, March 1979

C-1 Brackish ice; 69°25'30"N; 133°06'30"W, approximately 3 km south-west of Tuktoyaktuk.

- Impulse radar overflights, 300 MHz.
- Impulse radar surface traverse, 80, 300, and 400 MHz.
- NRC electrical properties - parallel rod capacitive measurements.
- NRC radar overflights - parallel and perpendicular polarizations.
- GSC borehole radar in two vertical planes at right angles.
- GSC time-domain reflectometry on two vertical planes at right angles.
- Augered holes for ice thickness.
- Cores for salinity, crystal and density analysis.
- SURSAT overflights and surface radiometry.
- Low level aerial photography.
- Threshold water current measurement.

C-2 Land-fast, first-year sea ice; 69°51'N; 132°00'W; approximately 60 km north-east of Tuk.

- Impulse radar overflights, 300 MHz.
- Impulse radar surface test for anisotropic ice, 300 MHz.
- Augered holes for ice thickness.
- Cores for analysis.
- Ice temperature profile consisting of two separate profile measurements, one for the top 1 meter, the second for the bottom 1 meter with at least one point extending into the water column. Surface profile distance intervals were 10 cm; bottom profile increments approached 2 cm separation at the ice/water interface. Continuously recorded March 11 to March 25.
- SURSAT overflights.
- Low level aerial photography.
- Threshold water current measurements.

C-3 Fresh water pond; 69°30'N; 132°38'W; approximately 18 km north-east of Tuk.

Sometimes referred to by C-CORE party as "SURSAT pond".

- Impulse radar overflights, 80 and 300 MHz.
- SURSAT overflights and augered ice thickness holes.
- Low level aerial photography.

C-4 Land-fast, first-year sea ice; 70°00'N; 132°00'W; approximately 70 km north-east of Tuk.

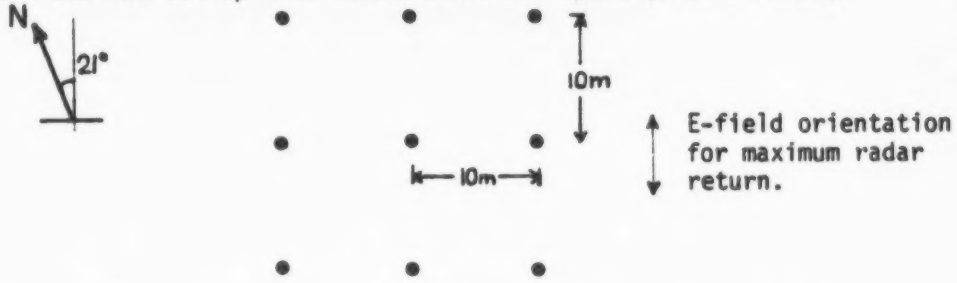
Also known as "Site A" by SURSAT team.

- Impulse radar overflights, 80 and 300 MHz.
- Impulse radar surface traverses for anisotropic studies, 300 MHz and 400 MHz bistatic.

Table 5. Site Locations and Data Collected (cont'd)

- NRC electrical properties
- GSC borehole radar at one grid intersection, two planes.
- GSC time-domain reflectometry at each grid intersection, two planes.
- Impulse radar wide angle reflection and refraction on two planes at 90° with and without snow cover.
- Augered holes for ice thickness.
- Cores taken at each of nine grid intersections, plus some additional points.
- Temperature profiles at 10 cm intervals from the surface to the ice-sea water interface.
- SURSAT overflights and surface truth data.
- Low level aerial photography.
- Threshold water current measurements.

A square grid 20m x 20m was set up with cores taken 10m apart (i.e. 9 cores).



The grid was aligned to the maximum impulse radar return.

C-5 First-year ice; southern edge of newly refrozen lead a few km north of C-4 along 132°W.

- Impulse radar overflight, 300 MHz.
- Cores taken for analysis.
- SURSAT overflights.

C-6 First-year ice; northern edge of newly refrozen lead, approximately 8 km north of C-5.

- Impulse radar overflight, 300 MHz.
- Cores taken for analysis.
- SURSAT overflights.

"Multi-year" - Multi-year ice floes located in vicinity of ice island T-3. Same area as SURSAT multi-year site.

- Impulse radar overflight, 80 and 300 MHz.
- Impulse radar wide angle reflection and refraction in one plane over two ice types, 80 MHz.
- Impulse radar surface profiling, 80 and 300 MHz.

cont'd...

Table 5. Site Locations and Data Collected (cont'd)

- Augered holes for ice thickness.
- Cores for salinity measurements.
- SURSAT overflights and surface truth data.
- Low level aerial photography.
- High level aerial photography (Esso).

Issungnak - Ice rubble field; 70°01'59.93"N; 134°18'50.62"W; approximately 72 km north-west of Tuk.

- Impulse radar overflights, 80 and 300 MHz.
- Low level aerial photography.
- SURSAT overflights.

Kugmallit Bay - main bay west of Tuk. Ice salinity appears to grade from brackish to typical first-year.

- Impulse radar overflights, 80 and 300 MHz.
- NRC radar overflights to Toker Pt.
- SURSAT overflights.

PCSP Pond - small frozen fresh water pond located immediately adjacent the Polar Continental Shelf Project base camp on the opposite side of the main road.

- Impulse radar antenna tests.
- Augered thickness.
- NRC electrical properties.
- NRC radar overflights.
- SURSAT overflights and surface radiometry.

T-3 - Free drifting glacial ice island; 72°37'N; 131°34'W (March 15, 1979 OMEGA position).

- Impulse radar overflights, 300 MHz.

APPENDIX I:

Impulse Radar Data Index

Impulse Radar Data Index Master Sheet - 1

File #	Date	Data Tape #	Location	Antenna Frequency (MHz)	Mode	Description	Photography
D-AT-IR TUK 79 #1	Mar. 8	79-1	Fuel Site/PCSP Pond/K. Bay	400	Bell 205 Bistatic	Initial test	B&W Film 1
	Mar. 8	79-1	Kugmallit Bay	80 (C-CORE built)	Bell 205 T/R 705 DAX	5 runs	
D-AT-IR TUK 79 #2	Mar. 9	79-2	C-3/K. Bay/Pingos	300 (shielded)	Bell 205	Data runs	B&W Film 1
D-AT-IR TUK 79 #3	Mar. 9	79-3	Toward Issungnak	300 (shielded)	Bell 205	Data run	
D-AT-IR TUK 79 #4	Mar. 9	79-4	Issungnak and return	300 (shielded)	Bell 205	Data run	
D-AT-IR TUK 79 #5	Mar. 10	79-5	Along 132°W	300 (shielded)	Surface	Anisotropy tests on ground	
	Mar. 11	79-5	Pond at PCSP Base Camp	---	Surface	Antenna tests	
D-AT-IR TUK 79 #6	Mar. 12	79-6	Along 132°W, N. from C-2	300 (shielded)	Bell 205	Reconnaissance, ½ hr. over 1st. year ice	B&W Film 2
D-AT-IR TUK 79 #7	Mar. 12	79-7	Along 132°W, S. from C-6	300 (shielded)	Bell 205	Data run	
	Mar. 13	79-7	Kugmallit Bay	300 (shielded)	Otter	Otter test	
D-AT-IR TUK #8	Mar. 14	79-8	Multi-year (T-3)	300 (shielded)	Otter	Day 1	B&W Film 2

Impulse Radar Data Index Master Sheet - 2

File #	Date	Data Tape #	Location	Antenna Frequency (MHz)	Mode	Description	Photography
D-AT-IR TUK 79 #9	Mar. 14	79-9	Multi-year (T-3)	300 (shielded)	Otter	Day 1	B&W Film 2
D-AT-IR TUK 79 #10	Mar. 14	79-10	Multi-year (T-3)	300 (shielded)	Otter	Day 1	B&W Film 3
D-AT-IR TUK 79 #11	Mar. 14	79-11	Over T-3	300 (shielded)	Otter	Day 1 over ground truth site	B&W Film 3
D-AT-IR TUK 79 #12	Mar. 15	79-12	T-3	300 (shielded)	Surface	Ground truth site	
	Mar. 15	79-12	T-3	80 (C-CORE built)	Surface Bistatic	Ground truth site	
	Mar. 16	79-12	PCSP Base Camp	500 ns calibrator	---	Calibration test	
D-AT-IR TUK 79 #13	Mar. 17	79-13	Multi-year (T-3)	300 (shielded)	Otter	Day 2 (leg 1)	B&W Film 2b and stereo
D-AT-IR TUK 79 #14	Mar. 17	79-14	Multi-year (T-3)	300 (shielded)	Otter	Day 2 (leg 2)	B&W Film 2b and stereo
D-AT-IR TUK 79 #15	Mar. 17	79-15	Multi-year (T-3)	300 (shielded)	Otter	Day 2 (leg 3)	Stereo
D-AT-IR TUK 79 #16	Mar. 17	79-16	Multi-year (T-3)	300 (shielded)	Otter	Day 2 (leg 4)	
D-AT-IR TUK 79 #17	Mar. 17	79-17	Multi-year (T-3)	300	Otter	Day 2 (leg 4)	
D-AT-IR TUK 79 #18	Mar. 17	79-18	Over T-3	300 (shielded)	Otter	Day 2 over ground truth site	B&W Film 5

Impulse Radar Data Index Master Sheet - 3

File #	Date	Data Tape #	Location	Antenna Frequency (MHz)	Mode	Description	Photography
D-AT-IR TUK 79 #19	Mar. 18	79-19	C-1 (ice road)	300 (shielded)	Surface	Profile	
	Mar. 18	79-19	C-1 (ice road)	80 (GSSI)	Surface Bistatic	Profile	
	Mar. 18	79-19	C-1 (ice road)	300 (shielded)	Surface	Profile	
	Mar. 18	79-19	C-1 (ice road)	400	Surface Bistatic	Traverse and antenna rotation	
D-AT-IR TUK 79 #20	Mar. 20	79-21	C-4	300 (shielded)	Surface	20, 50 and 100 ft. runs	
	Mar. 20	79-21	C-4	300 (shielded)	Bell 205	Equipment and ground test	
	Mar. 20	79-21	PCSP Base Camp	80 (GSSI)	Surface Bistatic & T/R	Test run without "Eccosorb"	
D-AT-IR TUK 79 #21	Mar. 21	79-22	Over C-1	80 (GSSI)	Bell 205 Bistatic 705 DAX/ 705 D	Test and data run with "Eccosorb"	
	Mar. 21	79-22	C-4	80 (GSSI)	Bell 205 Bistatic 705 DAX/ 705 D	Grid with reflectors runs 1-4 Reflector run (5)	IR Film 1
D-AT-IR TUK 79 #22	Mar. 22	79-23	C-4	80 (GSSI)	Bell 205 Bistatic 705 DAX/ 705 D		

Impulse Radar Data Index Master Sheet - 4

File #	Date	Data Tape #	Location	Antenna Frequency (MHz)	Mode	Description	Photography
D-AT-IR TUK 79 #22 (cont'd)	Mar. 22	79-23	Along 132°W, S. from C-4	80 (GSSI)	Bell 205 Bistatic 705 DAX/ 705 D	Flight towards Tuk	IR Film 1
	Mar. 22	79-23	Over C-3	80 (GSSI)	Bell 205 Bistatic 705 DAX/ 705 D	2nd data run over SURSAT pond	
D-AT-IR TUK 79 #23	Mar. 23	79-24	Issungnak	80 (GSSI)	Bell 205 Bistatic 705 DAX/ 705 D	2nd set of data runs Ridge Profile Imperial Ice Island	B&W Film 6 B&W Film 6
D-AT-IR TUK 79 #24	Mar. 23	79-25	Multi-year (T-3)	80 (GSSI)	Bell 205 Bistatic 705 DAX/ 705 D	Runs 1 to 8 over ground truth site	IR Film 2
D-AT-IR TUK 79 #25	Mar. 23	79-26	Multi-year (T-3)	80 (GSSI)	Surface Bistatic 705 DAX/ 705 D	WARR	Ground truth photos, 70 mm
D-AT-IR TUK 79 #26	Mar. 25	79-27	C-4	400	Surface Bistatic	WARR runs 1-4	
	Mar. 25	79-27	C-4	300 (shielded)	Surface	Anisotropy exp't. run 5	
	Mar. 25	79-27	C-4	400	Surface Bistatic	Anisotropy exp't. runs 6 and 7	
	Mar. 25	79-27	C-4	300 (shielded)	Surface	Anisotropy exp't. run 8	

APPENDIX II:

International Workshop on Remote
Estimation of Sea Ice Thickness

First Circular, May 1979

C-CORE
CENTRE FOR COLD OCEAN RESOURCES ENGINEERING
MEMORIAL UNIVERSITY OF NEWFOUNDLAND
ST. JOHN'S, NEWFOUNDLAND, A1B 3X5, CANADA
TELEPHONE (709) 753 1200

First Circular

INTERNATIONAL WORKSHOP ON REMOTE ESTIMATION OF SEA ICE THICKNESS

September 25 and 26, 1979

Memorial University of Newfoundland
St. John's, Newfoundland, Canada.

A recent questionnaire indicated considerable enthusiasm for a research workshop with the following goals:

(i) to review the state-of-the-art of remote ice thickness sounding, including recent field results;

(ii) to summarize current knowledge of the electrical properties of sea ice;

(iii) to review ice sounding technology; and,

(iv) to recommend directions for future research and development in this field.

A preliminary agenda is attached. Approximately four to six invited papers will be presented during each of Sessions 1 to 3. Ample time will be allowed for discussion. It is hoped that during Session 4 discussion will highlight the most important deficiencies in our present knowledge and indicate promising fresh approaches.

Preprints of invited papers will be available at registration, and a summary document will be produced following the workshop. Further information including a list of speakers and program details will be distributed in a Second Circular.

Participants are expected from Canada, U.S.A., England, U.S.S.R. and other Western European countries. In order to facilitate discussion, the number of attendees will be limited. Those wishing to participate are urged to return the attached form as soon as possible.

For more information, contact Dr. James R. Rossiter, C-CORE, Memorial University of Newfoundland, St. John's, Newfoundland, Canada A1B 3X5 Phone: 709-.53-1200 extensions 3733 or 3872.

May 1979

International Workshop on Remote Estimation of Sea Ice Thickness

Preliminary Agenda - May 1979

Monday, September 24, 1979

Evening - The traditional "icebreaker" reception

Tuesday, September 25, 1979

Morning - Session 1: Summary of recent field results
Afternoon - Session 2: Electrical properties of sea ice
Evening - Reception and dinner

Wednesday, September 26, 1979

Morning - Session 3: Ice sounding radar technology
Afternoon - Session 4: Discussion - future directions
Evening - free

Thursday, September 27, 1979

Optional tours can be arranged for those interested.

Organizing Committee

Mr. M.P. Bruce-Lockhart, Associate Professor
Faculty of Engineering
Memorial University of Newfoundland
St. John's, Nfld. A1B 3X5

Mr. D.M. Grenville, Administrator
Centre for Cold Ocean Resources Eng.
Memorial University of Newfoundland
St. John's, Nfld. A1B 3X5

Dr. S.K. Parashar, Vice-President
REMOTEC Applications Inc.
P.O. Box 5547
St. John's, Nfld. A1C 5W4

Dr. D.I. Ross, Director of Operations
NORDCO, Ltd.
P.O. Box 8833
St. John's, Nfld. A1B 3T2

Dr. J.R. Rossiter, Leader, Ice Detection Group (Chairman)
Centre for Cold Ocean Resources Engineering
Memorial University of Newfoundland
St. John's, Nfld. A1B 3X5

The workshop will be sponsored by C-CORE, with assistance from the above groups and financial support from the Government of Canada.

International Workshop on Remote Estimation of Sea Ice Thickness

September 25 and 26, 1979
St. John's, Newfoundland

REPLY FORM

Name (please print): _____

Organization: _____

Address: _____

_____

Phone: _____

I expect to participate in the above workshop Yes ____

No ____

Note: Although it is not anticipated that there will be a registration fee associated with the technical workshop, there may be a charge to cover meals and entertainment.

Please reserve a single room for me at the Hotel Newfoundland for

September 24 _____

September 25 _____

September 26 _____

I would be interested in participating in optional tours on September 27 ____

Further comments:

Please return as soon as possible, but before September 1, 1979, to:

Ice Thickness Workshop
C-CORE
Memorial University of Nfld.
St. John's, Newfoundland
Canada A1B 3X5

POOR

QUALITY

ORIGINAL